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ATOMATIC X-RAY DIFFRACTION MACHINE MEASUREMENT OF RESIDUAL STRESS IN ALUMINUM ALLOYS

Donald H. Gray

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December 1975

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IN ALUMINUM ALLOYS

THESIS

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Fastress automatic x-ray diffraction machine measurement of stress in aluminum alloys is compared with stress determined by strain gage and conventional x-ray diffraction techniques. Modification of the Fastress specimen positioner and operating procedures were required for acceptable performance. The modified machine and procedures resulted in measurement of stress in 2024-T6 aluminum alloy with a maximum error of 3,400 psi and a mean error of 2,600 psi compared to the strain gage measurements.

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Fastress values agreed within 1,000 psi of residual stresses determined by conventional x-ray diffraction methods. Test of a shot-peened 2024-T6 aluminum alloy resulted in a maximum error of 4,600 psi and a mean error of 2,000 psi compared to a strain-gage-determined stress. Residual stresses for shot-peened specimens measured by Fastress were within 2,500 psi of the value measured by the conventional x-ray diffraction machine. Limited testing of anodized 2024-T6 and 7171-T6 aluminum alloy resulted in mean errors up to 8,000 psi; the maximum error was 11,000 psi. These errors may be able to be reduced by selecting a proper stress factor. It can be concluded that the modified Fastress technique can measure stress in aluminum alloys with a mean error of 2,500 psi, or less, if the proper stress factor is used.

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AUTOMATIC X-RAY DIFFRACTION MACHINE
MEASUREMENT OF RESIDUAL STRESS IN ALUMINUM ALLOYS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

Donald H. Gray, B.M.E.
Graduate Aeronautical Engineering

December 1975

Preface

This study was undertaken to evaluate the use of a Fastress automatic x-ray diffraction machine for measurement of residual stress in parts made of aluminum alloy. Since Fastress has not been extensively used for this purpose, a major part of the study involved the development of suitable test procedures. It is hoped that the results obtained will be considered and expanded upon by future investigators; hopefully this will culminate in the development of a reliable method for rapid residual stress analysis in aluminum-alloy components.

The research was performed at the Air Force Materials Laboratory (AFML), Wright-Patterson Air Force Base, Ohio. The assistance and sponsorship of Mr. Lee Gully and Mr. Grover Hardy of AFML is gratefully acknowledged. I would also like to thank Mr. Vijay Rastogi of the B. F. Goodrich Company and Mr. Hal Miller of the Goodyear Aerospace Company for their assistance and suggestions in preparing test specimens. Thanks are also due Mr. Paul Prevay of Metcut Research Associates, Inc. for his assistance in the evaluation of test specimens. Finally I especially wish to acknowledge the guidance, assistance, and encouragement of my thesis advisor, Lt. Col. James A. Snide.

Donald H. Gray

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Abstract

Fastress automatic x-ray diffraction machine measurement of stress in aluminum alloys is compared with stress determined by strain gage and conventional x-ray diffraction techniques. Modification of the Fastress specimen positioner and operating procedures were required for acceptable performance. The modified machine and procedures resulted in measurement of stress in 2024-T6 aluminum alloy with a maximum error of 3,400 psi and a mean error of 2,600 psi compared to the strain gage measurements. Fastress values agreed within 1,000 psi of residual stresses determined by conventional x-ray diffraction methods. Test of a shot-peened 2024-T6 aluminum alloy resulted in a maximum error of 4,600 psi and a mean error of 2,000 psi compared to a strain-gage-determined stress. Residual stresses for shot-peened specimens measured by Fastress were within 2,500 psi of the value measured by the conventional x-ray diffraction machine. Limited testing of anodized 2024-T6 and 7171-T6 aluminum alloy resulted in mean errors up to 8,000 psi; the maximum error was 11,000 psi. These errors may be able to be reduced by selecting a proper stress factor. It can be concluded that the modified Fastress technique can measure stress in aluminum alloys with a mean error of 2,500 psi, or less, if the proper stress factor is used.

AUTOMATIC X-RAY DIFFRACTION MACHINE MEASUREMENT OF RESIDUAL STRESS IN ALUMINUM ALLOYS

I. Introduction

Background

Automatic x-ray diffraction machines have recently been developed to provide rapid measurement of residual stress of steel. An example of this is the Fastress system developed by the General Motors Research Laboratory. A measurement that requires about one hour using conventional x-ray diffraction equipment can be completed by Fastress in about two minutes (Ref 10:6). Fastress was designed to be used on hardened steel parts but, theoretically, appears to have application for measuring residual stresses in aluminum alloys. Due to the large amount of high-strength aluminum alloy used in a wide variety of military and commercial applications, development of this capability is desirable.

The Air Force Materials Laboratory (AFML) recently purchased a Fastress machine for residual stress analysis. This machine was manufactured by the American Analytical Corporation under a license from the General Motors Corporation. Limited instruction for use of the machine on aluminum-alloy components was provided by American Analytical. Initial testing produced results of questionable accuracy and indicated a need for studying the feasibility of using

Fastress for measuring residual stresses in aluminum alloys. The purpose of this report is to present the results of this study.

Literature Survey

Developers of the Fastress system report that the method was developed primarily for measuring residual stresses in hardened steel. They claim that only minor modification should be needed in order to adapt the technique to aluminum alloys. It is estimated that the development unit will measure residual stress in steel with an accuracy of ±3,000 psi if a three-minute reading period is used. An accuracy of ±10,000 psi is estimated if reading time is limited to 20 seconds (Ref 11:90). Sturrock has reported on the use of Fastress for measuring residual stresses in aircraft parts. He reports the accuracy of stress readings to be within ±10,000 psi or better, but suggests that additional experimental work remains to be done, especially with regard to improving reliability (Ref 10:7). The American Analytical Corporation indicates that the Fastress machine can be used for measurement of stress in aluminum alloys and suggests some machine settings to be used (Ref 1:10).

Evaluation of the x-ray diffraction method of residual stress analysis has been the subject of many studies. The Society of Automotive Engineers, Inc. has reviewed many of the investigations and developed a handbook to consolidate results and to recommend standard procedures (Ref 2).

Several investigations have been directly concerned with application of x-ray diffraction to measurement of stress in aluminum alloys. Larson investigated the selection of conditions for aluminum stress measurement. He concluded that the most reliable method of calibration is to relate the x-ray readings to strain gage readings of an externally-stressed specimen. He tested 2014 aluminum alloy and concluded that reproducibility of the method to be within ±1,000 psi (Ref 4:35). Hilley, Wert, and Goodrich also studied the selection of x-ray diffraction conditions for measurement of stress in aluminum alloys. Calibration was accomplished by use of externally-stressed samples of 5083 aluminum alloy. An error of ±800 psi was noted (Ref 3:291). Swartzbart used x-ray diffraction to measure stress in 7075 aluminum alloy. Accuracy is estimated to be within ±2,000 psi (Ref 9:30).

The general concept of use of the x-ray diffraction technique for measurement of stress in aluminum-alloy components is well established. If the proper conditions are selected for measurement, it appears that the method can be accurate to within ±1,000 psi. Experimental methods used to verify this accuracy appear suitable for a similar evaluation of Fastress.

Problem Definition

The basic approach used to verify the suitability of x-ray diffraction stress measurement is to compare the

results with strain gage measurements of an externally-loaded specimen. This not only shows the ability of the method to detect changes in stress, but also provides calibration factors. A major portion of this study is devoted to this approach. Fastress readings are compared to strain gage measurements of a specimen in four-point bending. Aluminum alloys 1100, 2014, 2024, and 7178 were evaluated. The effect of surface finish was considered by evaluating specimens that had been shot-peened and specimens that had been anodized. Fastress measurements of some specimens are compared with residual-stress measurements by a calibrated conventional x-ray diffraction machine.

This study is limited to evaluation of the ability of Fastress to measure stress in aluminum without major modification of the machine. The x-ray wavelength and diffraction line used were selected because they are the only set compatible with the machine geometry. Use of the diffraction line recommended for stress measurement of aluminum alloys would require considerable mechanical modification of the machine to provide the required operating range. The results represent x-ray diffraction stress measurement at less than optimum conditions.

This report includes a review of x-ray diffraction stress measurement theory, a description of the test apparatus and procedures, discussion of test results, conclusions and recommendations.

II. Theory

X-Ray Diffraction

Discussion of x-ray diffraction theory requires first a review of the atomic structure of metals. The ideal metal is considered to consist of randomly packed crystalline grains. In each crystalline grain, the atoms are arranged in parallel and equally spaced planes. The perpendicular distance between the adjacent planes in the unstrained crystal is a basic property of the material. Application of a stress causes a change of this spacing by an amount dependent upon the orientation of the plane to the stress (Ref 8:23A).

Application of x-rays to the surface of a metal results in diffraction of the x-ray at an angle dependent upon the spacing of the atomic planes and the wavelength of the x-ray. The mathematical relationship for this phenomenon is known as Braggs law. It may be expressed:

$$d = \frac{\lambda}{2 \sin \theta} \tag{1}$$

Where λ is x-ray wavelength,

θ is diffraction angle,

d is spacing of the atomic planes.

Measurement of the diffraction angle θ is the basis for all x-ray diffraction stress measurement methods.

Stress Measurement By X-Ray Diffraction

The theory of elasticity can be used to show that the stress in a metal is proportional to the difference between the diffraction angles measured during two different x-ray exposures. One measurement is made of planes parallel to the surface. A second is made of planes at some angle of inclination to the surface. The angle of inclination is usually 45 or 60 degrees. The constant of proportionality is called the stress factor. The stress factor is a function of the material elastic constants and the x-ray measurement geometry. Figure 1 illustrates the geometry and terminology of x-ray diffraction stress measurement.

Mathematical derivation of the stress measurement relationship is readily available (Ref 2:13-15) and will not be repeated here. The relationship may be expressed:

$$\sigma_{\phi} = \left(\frac{d_{\psi} - d_{\perp}}{d_{\perp}}\right)\left(\frac{E}{1+\nu}\right)\frac{1}{\sin^2\psi} \tag{2}$$

Where σ_{ϕ} is stress in the plane of measurement,

$d_{\perp}$ is spacing of planes parallel to the surface,

d_{ψ} is spacing of planes at angle to the surface,

E is Young's modulus,

ν is Poisson's ratio,

ψ is angle of the inclined planes.

This equation is considered to give the most accurate results, but is frequently reduced to the form:

$$\sigma_\phi = K\left(2\theta_\perp - 2\theta_\psi\right) \tag{3}$$

Where
$$K = \left(\frac{\mathrm{Cot}\,\theta}{2}\,\frac{E}{1+\nu}\,\frac{1}{\mathrm{Sin}^2\psi}\right) = \text{stress factor} \tag{4}$$

$\theta_\perp$ is diffraction angle from planes parallel to the surface,

θ_ψ is diffraction angle from planes inclined to the surface.

It has been found that the difference in results between Eqs (2) and (3) is insignificant over the stress range 1 to 50ksi (Ref 2:111).

Stress measurement by x-ray diffraction consists of two basic problems: determination of the x-ray diffraction angle for two measurements and selection of the proper stress factor. Both are somewhat more difficult than would appear. Problems arise in measurement of the exact diffraction angle because this requires the determination of the point of maximum diffracted intensity which may not be well defined. Frequently, the intensity is nearly constant for a diffraction angle of several degrees. Some distortion of the diffracted x-ray intensity pattern also occurs during measurement of the planes that are inclined to the surface. Experience has indicated that standard analysis techniques are required to provide acceptable reproducibility. A handbook developed by the Society of Automotive Engineers is a good source of the required analysis procedures (Ref 2).

The stress factor may be determined experimentally or computed from elastic constants. The experimental method

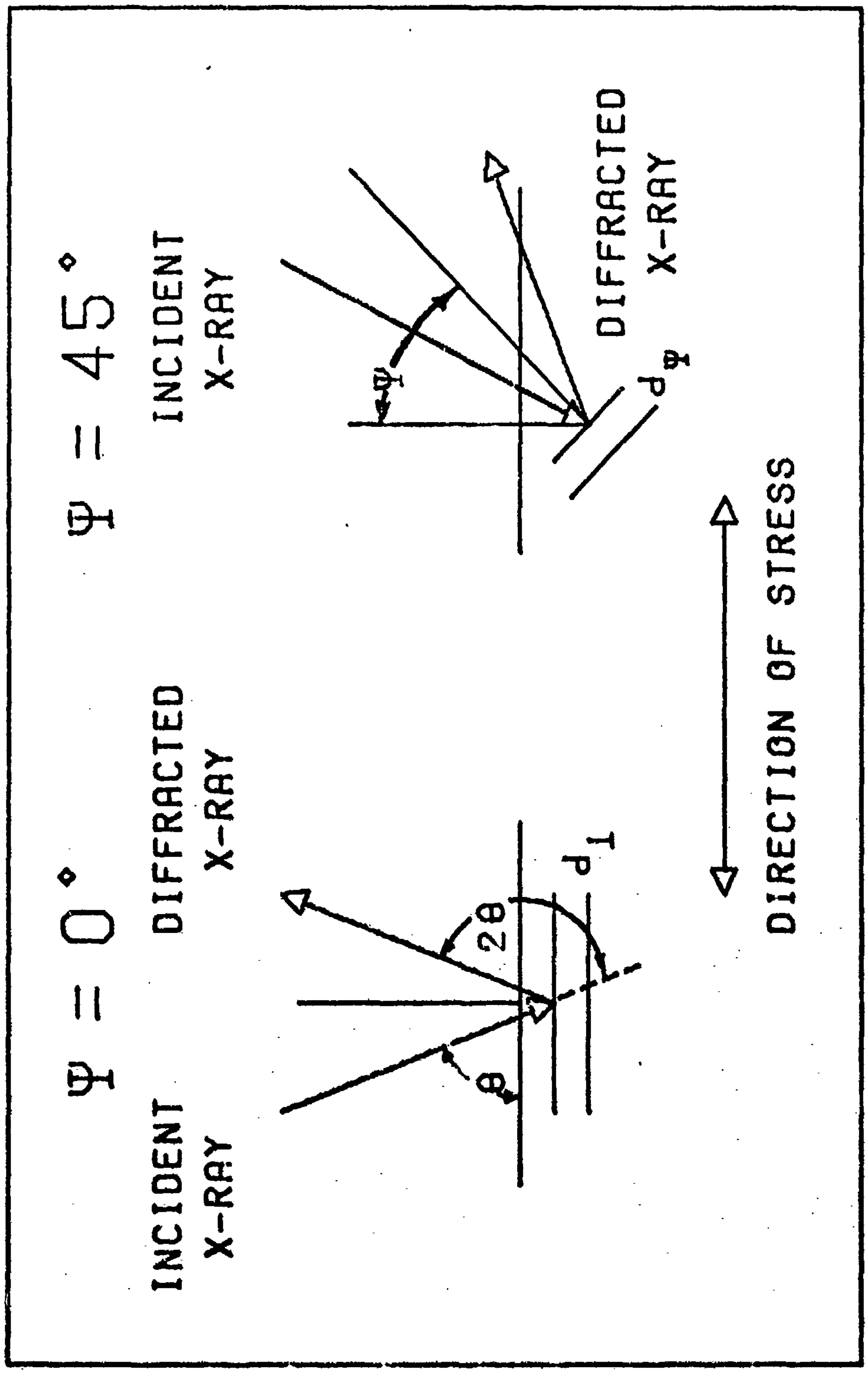

Fig. 1. X-ray Diffraction Geometry and Terminology

consists of relating the diffraction angle measurements to strain gage readings when a specimen is externally loaded. This is the preferred approach because the bulk value elastic constants may not be applicable to the particular direction of the atomic planes used for the x-ray diffraction measurement (Ref 2:46-47).

It should be noted that the stress computed from the x-ray diffraction measurement is an average value for the layer of material responsible for the diffraction. This layer is estimated to be about 0.002 inch thick for measurement of stress in aluminum with x-rays generated by a chromium target tube (Ref 4:34).

A major consideration in x-ray diffraction stress measurement is selection of the x-ray wavelength and the diffraction peak to be used. The wavelength is determined by the type of target tube used. Several diffraction peaks are produced for each wavelength depending upon the material being investigated. Intensity of the peaks usually decreases as the diffraction angle is increased. A diffraction angle (2θ) greater than 130 degrees is required for accurate stress measurement (Ref 3:286). When chromium x-ray tubes are used, the recommonded diffraction peak in the unstrained aluminum crystal occurs at 139.5 degrees. A peak also occurs at 156.9 degrees but it has an intensity that is about 30 per cent of the intensity of the 139.5 degree peak. Some investigators have concluded that only the 139.5 degree peak is suitable for stress measurement (Ref 4:33). The 156.9

degree peak has also been used with limited success (Ref 9:30). Copper and cobalt target tubes have also been used for stress measurement in aluminum. The recommended diffraction peak occurs at an angle of about 162.5 degrees for both the copper and cobalt radiation (Ref 3:287).

Fastress Operation

The Fastress machine differs from conventional x-ray diffraction stress measurement equipment in three major features. First, it has two x-ray sources and two detector systems. This permits simultaneous measurement of the angle of the diffracted beams from the planes at 0 and 45 degrees to the surface. Conventional machines have only one x-ray source and one detector that must be repositioned between the two readings. A second feature of Fastress is a mechanism that automatically positions the detectors at the center of the diffracted x-ray beam. Usually the center or peak is determined by manual analysis of a plot of diffracted beam intensity. The third feature is a stress computer that converts the difference between the two readings to a stress value that is plotted on a strip chart. The stress computer uses a stress factor that is manually set by the operator.

Since Fastress was designed to measure stress in hardened steel parts, some design factors have been selected for optimum performance for this application (Ref 11:90). Chromium target x-ray tubes are used. The machine is mechanically limited to measurement of diffraction angles (2θ) in

the range of 152 to 159 degrees. This means that the diffraction peak recommended for aluminum stress measurement at 139.5 degrees cannot be used. As noted before, the peak at 156.9 degrees is much less intense but has been used for measurement of stress in aluminum. The machine should be able to measure stress in aluminum; however, the low intensity may result in unstable operation and a sensitivity to variables such as surface finish.

III. Experimental Apparatus

Fastress

A Fastress Residual Stress Analyzer Model AA-100 was used for this investigation. This machine was manufactured by the American Analytical Corporation and delivered to the Air Force Materials Laboratory (AFML) in 1973. Figure 2 is a photograph of the machine. Appendix A contains a detailed description of the machine controls and the settings recommended for measurement of stress in aluminum. Modification of the Fastress during this study was limited to replacement of the specimen positioner with one made from nonmetallic material.

Loading Fixture

Figure 3 shows the Fastress with the special fixture used for the loaded specimen test. Figure 4 shows the machine side of the fixture with a specimen installed. The specimen is installed so that load can be applied to cause tensile stress in the surface facing the machine. The fixture also permits application of load to cause compressive stress. The fixture is mounted on a movable base to permit proper alignment with any loading condition. A lead sheet is used on the back of the fixture as a radiation shield.

Test Specimen

A calibration standard provided by American Analytical

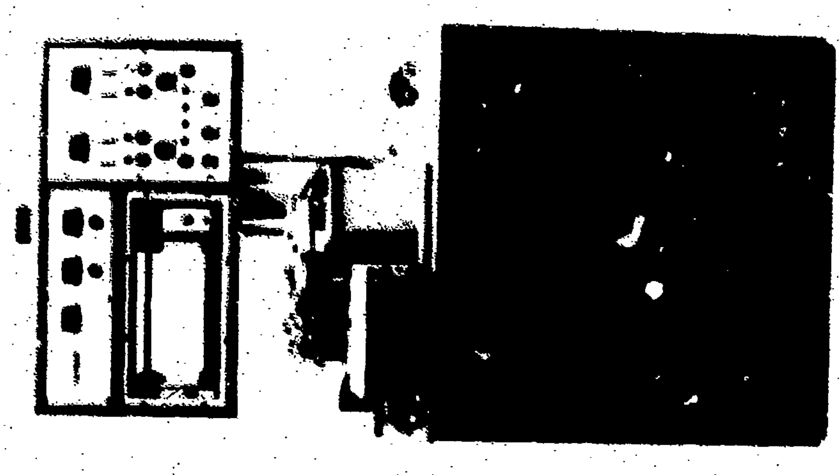

Fig. 2. Fastress Residual Stress Analyzer

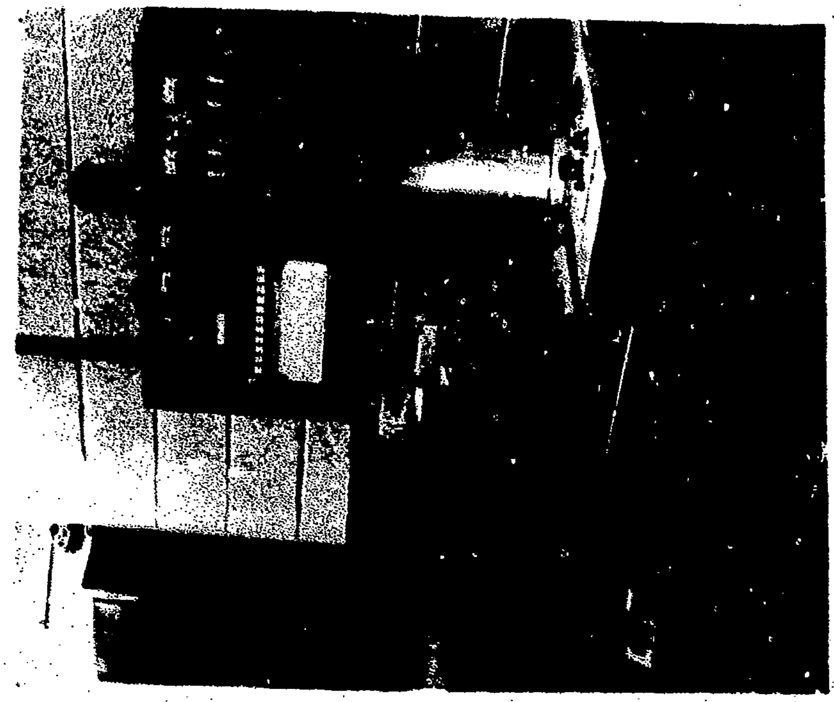

Fig. 3. Test Equipment Installation

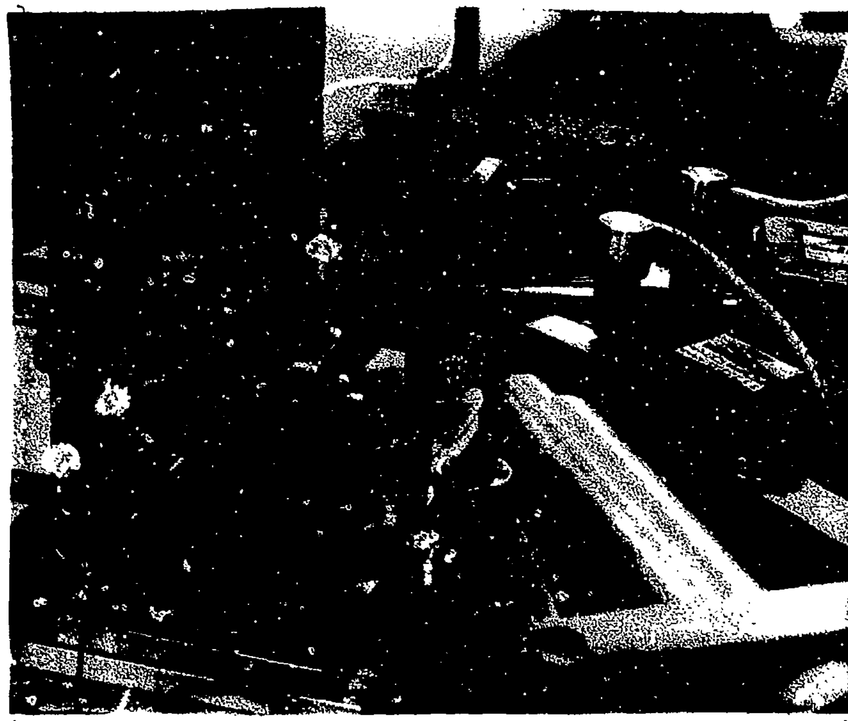

Fig. 4. Loading Fixture

Fig. 5. Test Specimen with Instrumentation

Corporation was used for the preliminary evaluation of Fastress. This standard is an aluminum plate with a grit blasted surface. Residual stress of the surface was determined by conventional x-ray diffraction stress measurement to be 16,000 psi compressive.

All specimens used for the loaded-sample test are 0.125-inch thick, one-inch wide, and seven-inches long. Figure 5 is a photograph of a typical specimen with instrumentation attached. Table I is a listing of the specific configurations evaluated.

Specimen Instrumentation

All specimens used for the loaded-sample test were instrumented with electric-resistance strain gages installed in the position shown in Fig. 5. SR-4 strain gages, manufactured by BLH Electronics, were used with a BLH switching and balancing unit model 225 and a BLH SR-4 strain indicator model 100P for strain measurements.

Table I

Test Specimen Index

Specimen	Alloy	Condition	Rockwell Hardness	Remarks
1100-2	1100	O	H30	--
2014-3	2014	O	H84	--
2014-4	2014	T-6	B87	--
2024-1	2024	T-6	B79	--
2024-2	2024	T-6	B79	--
2024-5	2024	T-6	B79	Anodized
2024-8	2024	T-6	B80	Shot Peened
2024-11	2024	T-6	B80	Shot Peened
2024-14	2024	O	H85	--
7178-2	7178	T-6	B87	--
7178-4	7178	O	H91	--

IV. Experimental Procedure

Fastress Procedure Evaluation

The purpose of this phase was to evaluate the suitability of the operating procedure recommended by the machine manual. The first part consisted of measurement of the calibration standard mounted in the sample fixture provided with the machine. The second part consisted of measurement of the calibration standard when installed in the special loading fixture used for the remainder of this investigation. In both cases, the standard of performance was the ability of Fastress to accurately indicate the rated value of the calibration standard.

Loaded-Specimen Test

The second phase of the study was comparison of changes in the Fastress reading with stress computed from strain-gage measurements of a specimen loaded in four-point bending. Fastress machine settings and operating procedures were as determined to be optimum from the first phase of the study. The standard of performance was the ability of Fastress to indicate changes in stress of the same magnitude indicated by the strain gages.

The 1100 and 2024 alloy specimens were cut from 0.125-inch thick plate and machined to the proper size. The 2014 specimens were machined from a section of an aircraft wheel forging. The 7178 specimens were machined from an aircraft

wing panel. All specimens were heat-treated to the proper condition in accordance with the requirements of Mil-H-6088E (Ref 6). Solution treatment conditions were as follows:

Alloy	Temperature (°F)	Time (Hours)
2014	935	1
2024	920	1
7178	870	1

All specimens were water-quenched after heating. Some specimens were then annealed by heating at 775°F for one hour. The temperature was then reduced at a rate of approximately 50 degrees per hour until a temperature of 500°F was reached. Specimens were then removed from the furnace and permitted to cool at a natural rate to room temperature.

The remaining 2014, 2024 and 7178 specimens were artificially aged to the T6 condition. The following conditions were used:

Alloy	Temperature (°F)	Time (Hours)
2014	350	10
2024	375	9
7178	250	24

Most specimens were evaluated with the surface finish existing after heat treatment. Some of the 2024-T6 aluminum specimens were given an anodic coating in accordance with Mil-A-8625C; a Type II (sulfuric acid bath) coating

was used (Ref 5). Shot-peening of both coated and uncoated specimens was accomplished in accordance with Mil-S-13165B (Ref 7). Specimens were peened on both sides with 0.033-inch cast steel shot at an intensity of 10-14 A2.

Strain-gage calibration curves were developed for each gage by loading the specimen in tension in a tensile test machine. The specimen was loaded to a maximum of approximately 80 per cent of the handbook yield stress for the material. Load was applied in equal increments of load and the indicated strain for each gage recorded. Stress was obtained by dividing the load by the cross-sectional area measured at the center of the specimen.

Fastress zero-reference values were obtained by installing the specimen in the fixture and tightening the load screws to the point that the strain indicators just started to move. The fixture was then moved toward the Fastress positioner until contact was made as indicated by movement of the strain indicators. Subsequent Fastress readings were made by moving the specimen away from the positioner, increasing load on the screws until the desired strain reading was obtained on each gage, and repositioning the specimen against the positioner. Equal increments of strain were used to a maximum value calculated to provide approximately eighty per cent of the yield stress for each specimen.

Fastress provides a variable reading as indicated by Fig. 6. This is the result of continuous detector arm searching for the point of peak intensity. Detector counting

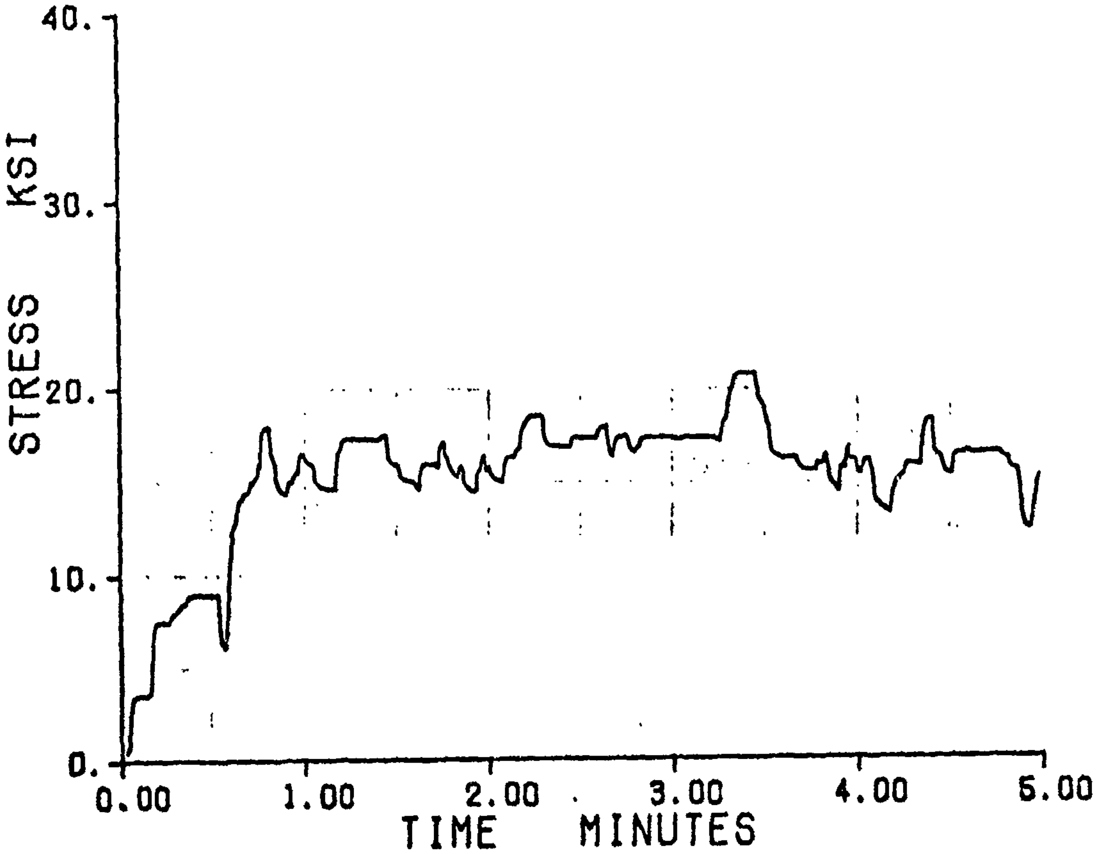

Fig. 6. Typical Fastress Stress Measurement Record

rate variations prevent full stabilization of the indicated stress. The amount of fluctuation depends not only upon the specimen but also the Fastress control settings.

The Fastress measurement shown for this study is the mean value indicated during a two-minute period following an initial stabilization period. The stabilization period is variable but always greater than two minutes. Stable readings, those within ±2,500 psi of a mean value, were determined by visual estimate. The mean of less stable measurements was determined by computation from the values recorded during equal time increments during the two-minute period. Measurements that fluctuated more than ±10,000 psi, that suddenly shifted from one stable value to another, or that resulted in the drive system going to the limit of the machine were considered unstable. The x-ray diffraction intensity plotting function was used to step-scan the diffraction peak to determine the cause of the instability.

Data Recording

Stress measurements were recorded on the integral chart recorder. Scale factors were modified to provide an expanded scale to facilitate data analysis. A scale of 10,000 psi per inch and a chart speed of 15 inches per hour was used for all stress measurements. The recorder was calibrated after a 30-minute warm-up period at the start of each test day.

Fastress intensity plotting was accomplished by using the integral recorder with a 30 inches per hour chart speed.

The intensity was step-scanned by manually positioning the detector in 0.2-degree increments and plotting the intensity at each point for 0.2 inch of chart movement.

Data Analysis

Fastress measurements were compared with the marked values of the calibration standard for phase one of this study. Machine settings and test configurations that provided mean stress values within ±2,000 psi of the marked value were considered acceptable. Conditions that resulted in greater error were investigated to determine the cause of error.

Data analysis for the second phase of the test consisted of comparison of the change in Fastress indications with the stress computed from the strain gage readings for each loading condition. The change in Fastress reading, called Fastress delta stress, was determined by subtracting the Fastress reading with no load applied from the Fastress reading with the load applied. The Fastress value is a mean value as discussed above. The value used for comparison, called gage stress, is the mean value of the stress computed for the two gages from the recorded strain values. Stress was computed using a calibration curve developed for each gage. Fastress delta stress values were plotted versus gage stress and compared with the line of perfect correlation to show performance of Fastress. In some cases a specimen was tested several times. This permitted determination of a

standard deviation to indicate the reproducibility of the measurement.

The accuracy of the absolute Fastress values was evaluated by comparison of the unloaded specimen measurements with stresses determined by Metcut Research Associates using calibrated conventional x-ray diffraction stress measurement equipment and methods.

V. Results and Discussion

Preliminary Evaluation

This phase of the study revealed two problems that resulted in the inability of Fastress to accurately measure the stress standard. These include severe interference of the two x-ray systems when operated simultaneously and distortion of the diffracted x-ray peak by the specimen positioner. Corrective modifications were developed. Additional minor modifications were developed to improve the ability of Fastress to measure stress in aluminum. These include the elimination of the vanadium filters, the use of increased servo gain and modification of the detector tube spacing.

Initial testing revealed that the $\psi = 45$ degrees x-ray source caused sufficient distortion of the x-ray diffraction of the $\psi = 0$-degree system to cause the $\psi = 0$-degree goniometer to be incorrectly positioned. This caused an error in the residual stress reading of about 5,000 psi. The Fastress manual suggests elimination of error by adjusting the zero position of the recorder to provide the correct calibration value. This is not a valid procedure because the amount of peak distortion is dependent upon the position of the $\psi = 0$-degree peak. The actual effect on the residual-stress reading is some nonlinear function. Adjusting for the error for the calibration sample may not provide the proper correction for other specimens.

It appears that the gating function built into the

Fastress should eliminate cross interference of the x-ray systems. Local trouble-shooting failed to identify any failure of the gating system. It was concluded that this system did not eliminate the interference. Testing was continued by using the Fastress in a semiautomatic mode. One system at a time was permitted to operate in the automatic positioning mode. The systems were manually switched at 30-second intervals to permit alternate operation. This eliminates the cross interference but decreases stability of the reading. Average total time for a stress measurement was six minutes. Simultaneous operation should reduce the time for a stable reading to about three minutes, as suggested by the literature (Ref 11:89).

The above procedure provided proper measurement of the calibration standard when mounted in the Fastress specimen stand. The measurement with the standard installed in the special loading fixture and with the Fastress specimen positioner was approximately 10,000 psi in error. This error was due to distortion of the diffracted x-ray by the metallic positioner. Substitution of a nonmetallic positioner of the same geometry eliminated the error.

The literature indicates that vanadium filters are not desirable for use on conventional x-ray diffraction machines for stress measurement in aluminum. Testing confirmed that the vanadium filters reduce the intensity of the diffracted x-ray by about 40 per cent and do not improve definition of the diffraction peak. The vanadium filters were removed for

all subsequent testing.

The servo gain setting determines the response of the goniometer positioning systems to changes in intensity gradient of the diffracted x-ray. Increasing the setting from the recommended 500 to 700 improved the rate of response without excessively increasing the fluctuation of the reading.

The Fastress operating manual recommends use of a four-degree detector tube spacing for measurement of stress in aluminum. The suitability of this setting was evaluated by plotting intensity of the diffracted x-ray versus the diffraction angle (2θ). Figure 7 is a plot of the ψ = 0-degree system for the calibration standard. Figure 8 is a plot of the ψ = 45-degree system for the standard. The four-degree setting means that when the detector arm is centered, each geiger tube is positioned at two degrees from the center of the peak. Inspection of the intensity plots reveals that this places the tube near the base of the peak in a region of low intensity gradient. This could result in an unstable and inaccurate stress reading. Reduction of the tube spacing to three degrees had little effect on the stress measurement. Apparently the stability of the stress measurement is more dependent upon the intensity fluctuations than changes in the intensity gradient. This may not be true for other specimens. It was concluded that the detector tube should remain at four degrees, but that suitability of this setting should be investigated for each

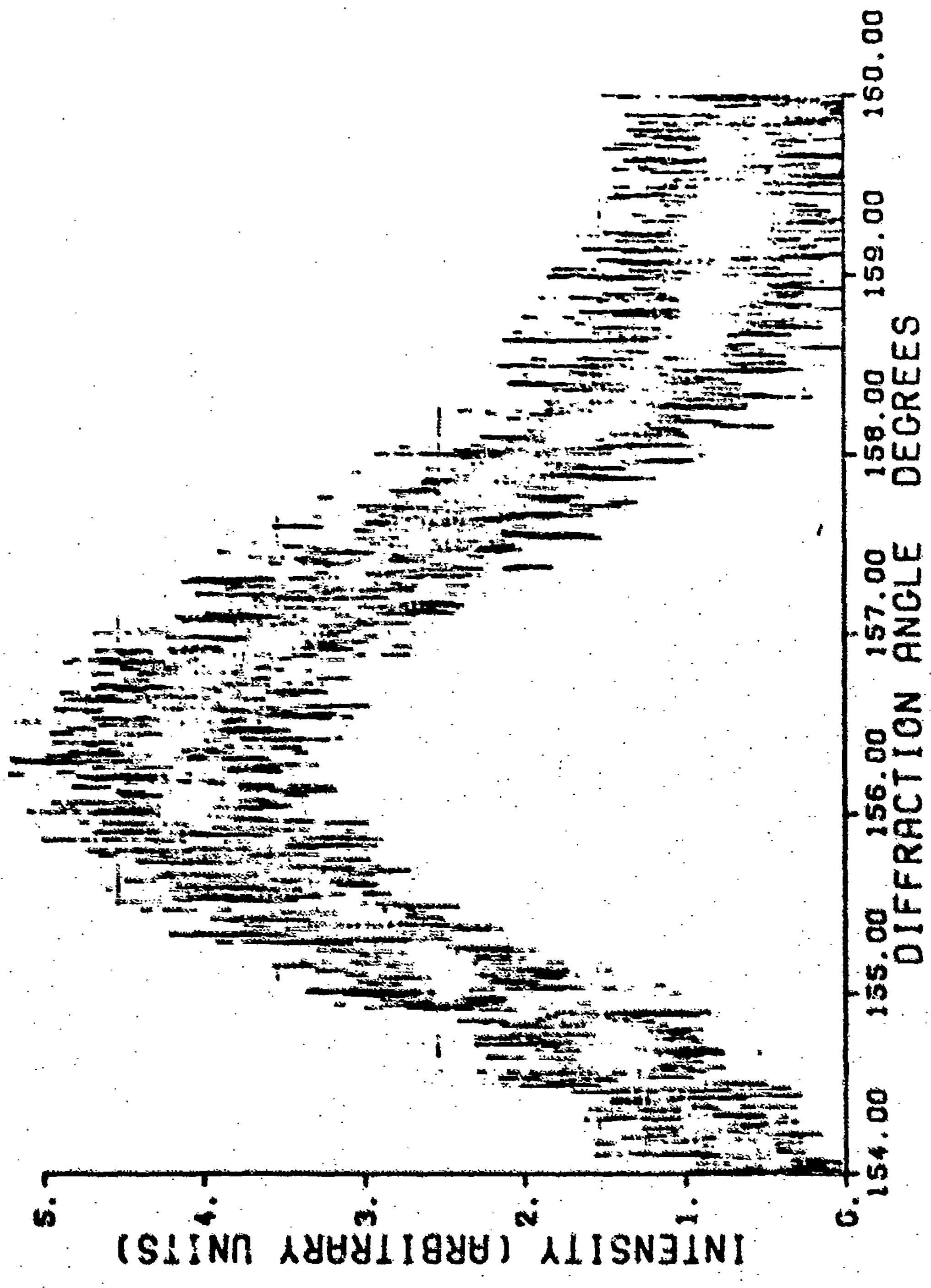

Fig. 7. Intensity Plot of ψ = 0-Degree System for the Calibration Standard

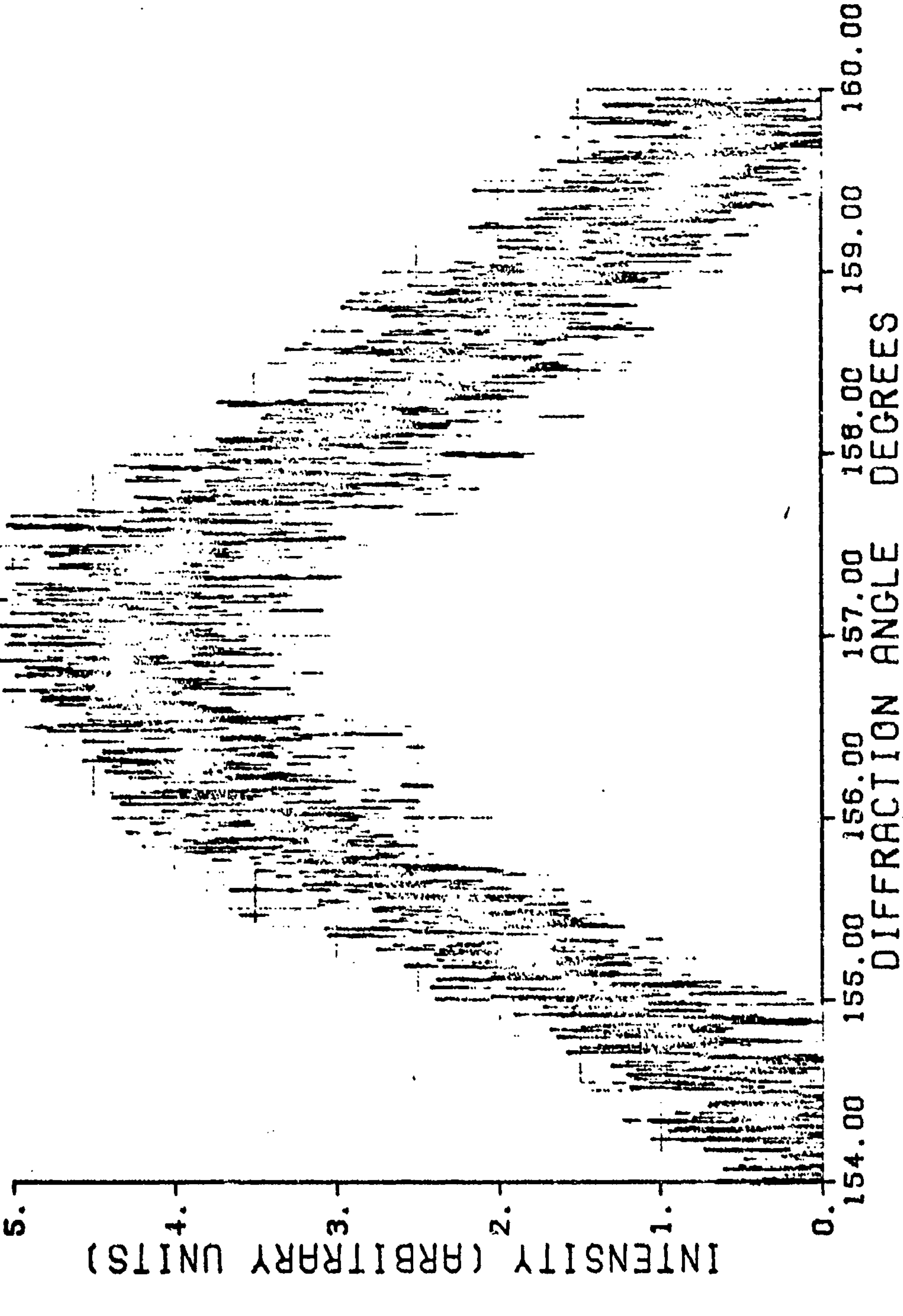

Fig. 8. Intensity Plot of Ψ = 45-Degree System for the Calibration Standard

specimen.

The conclusion of this phase of the investigation is that evaluation of the loaded specimens can be accomplished if the two x-ray systems are operated independently to avoid cross interference. A nonmetallic specimen positioner must be used; vanadium filters should be removed. The recommended machine settings are acceptable, except that a servo gain setting of 700 should be used to reduce the reading time. The four-degree detector tube spacing may not be suitable for all specimens but appears acceptable as a recommendation because it resulted in proper measurement of the calibration standard.

Loaded-Specimen Evaluation

The primary purpose of this phase of the study was to evaluate the ability of Fastress to measure changes in stress. The results also allow determination of the suitability of the recommended stress factor. Four basic categories of specimens were evaluated: fully annealed, heat-treated to the T6 condition, anodized, and shot-peened. Most of the testing was accomplished with 2024 aluminum alloy. Specimens of 1100, 2014, and 7178 were also evaluated in order to determine the effect of alloy variation.

Operation of Fastress in measurement of the annealed samples was somewhat erratic at low levels of applied stress. Application of 3,000 psi to the 1100 specimen was not detected by Fastress (Fig. 9). Performance was better for measurements of the 2014 specimen (Fig. 10) and the 2024

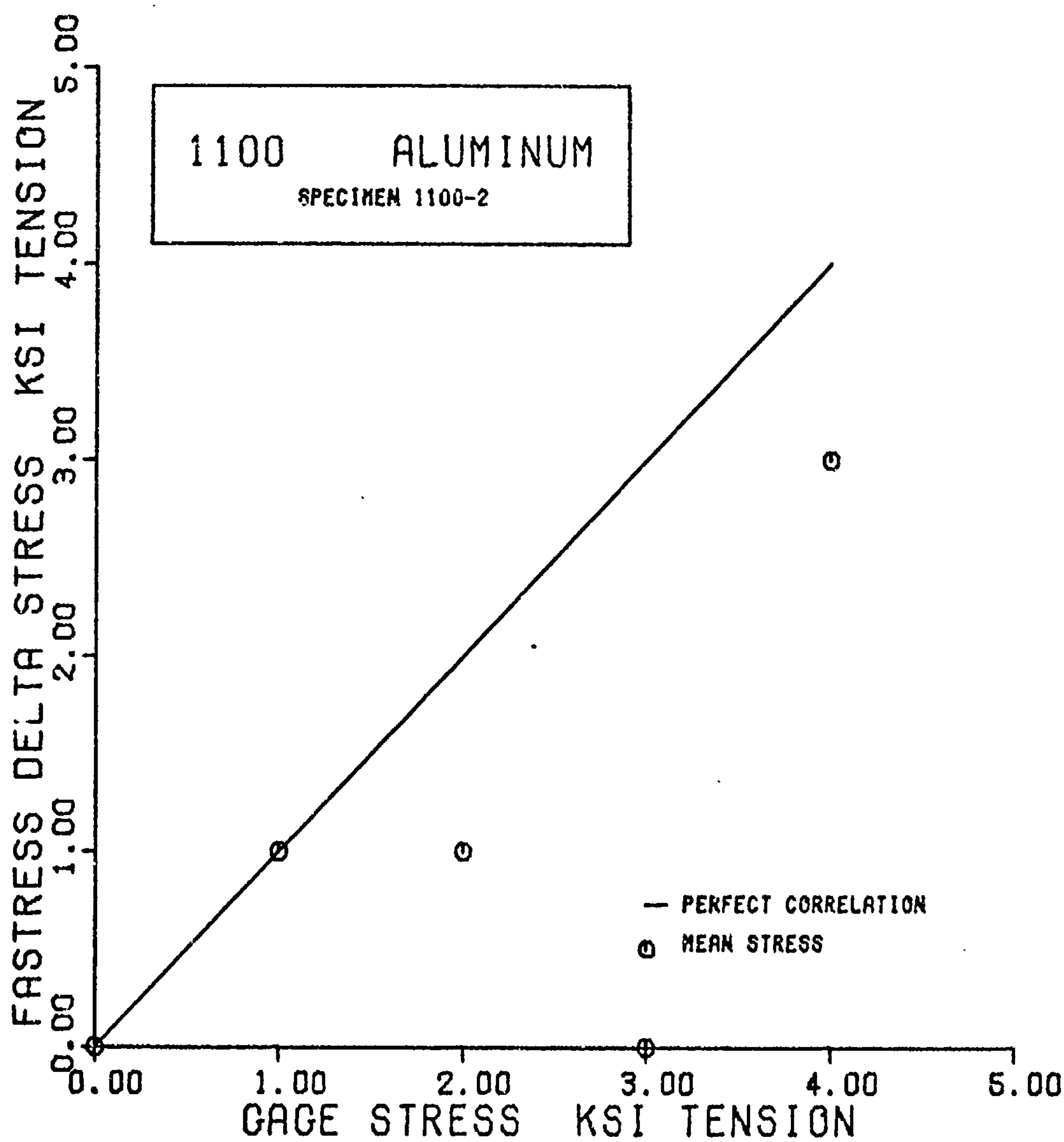

Fig. 9. Correlation Chart for 1100 Aluminum Alloy

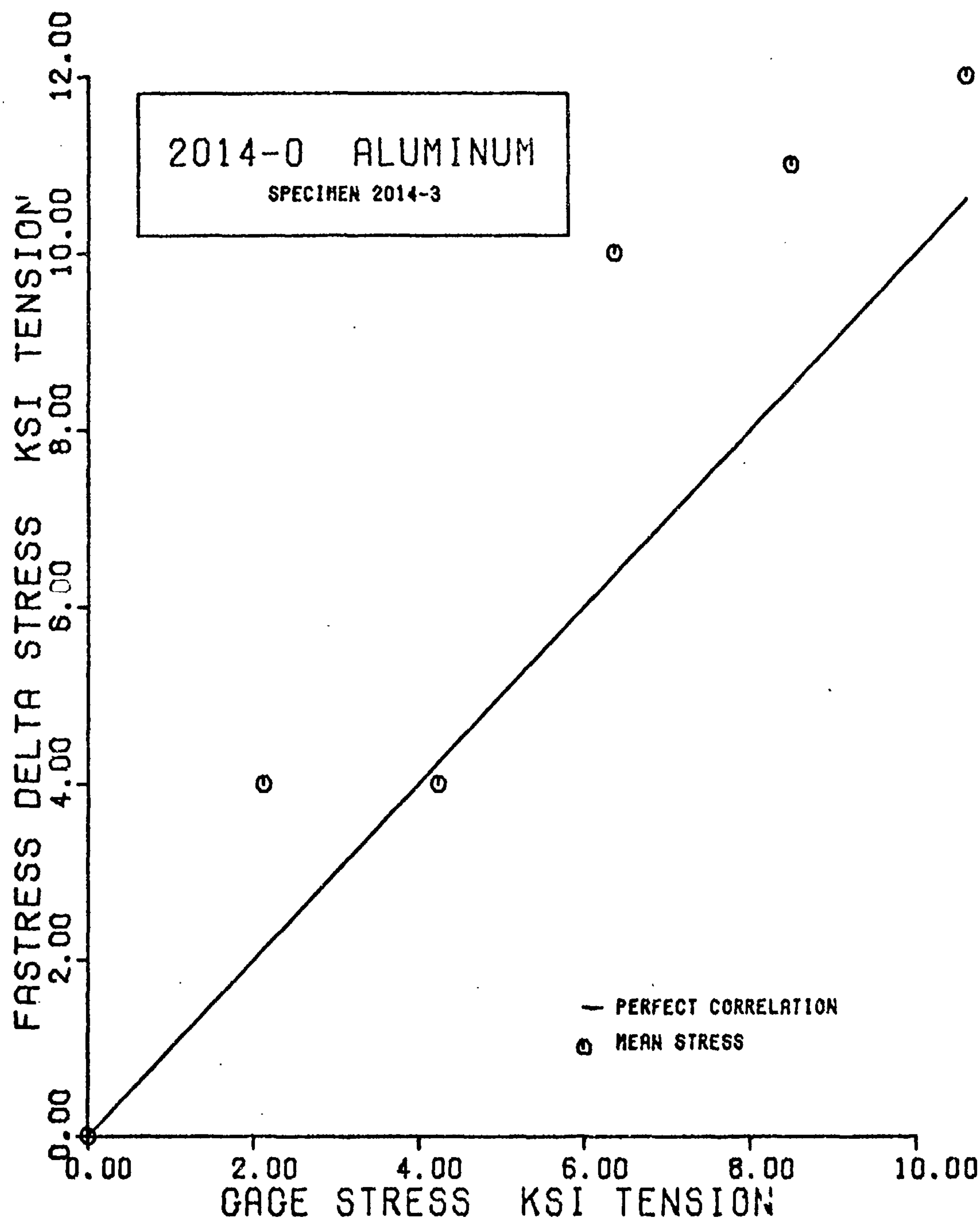

Fig. 10. Correlation Chart for 2014-0 Aluminum Alloy

specimen (Fig. 11). These tests indicated that the recommended stress factor is too high. It was not possible to obtain stable stress measurement of the 7178 specimen. It was concluded that the low level of applied stress which could be used with the annealed specimens was of the order of magnitude of the accuracy of Fastress. It was decided that testing should proceed immediately to the heat-treated specimens so that larger increments of applied stress could be used. The schedule did not permit further evaluation of Fastress performance on annealed specimens.

Two tests of the 2014-T6 specimen produced erratic results. Measurements were generally unstable and not reproducible (Fig. 12). A plot of the diffraction intensity revealed that the peaks were narrow compared to the peaks of the calibration standard (Figs. 13 and 14). It appeared that use of a two-degree detector tube setting would provide better results. Measurement with no load with the two-degree setting produced a stable stress value. Application of a load again produced unstable operation. This suggested that either the aluminum grains were large or that they had some preferred orientation such that the loading caused a significant change in the diffraction pattern. The specimen was rotated 180 degrees in a plane perpendicular to the x-ray sources, and the diffraction pattern again plotted. This revealed that the ψ = 45-degree peak was almost nonexistent (Fig. 15). This indicates that the specimen has a preferred grain orientation. This was confirmed by evaluation of the

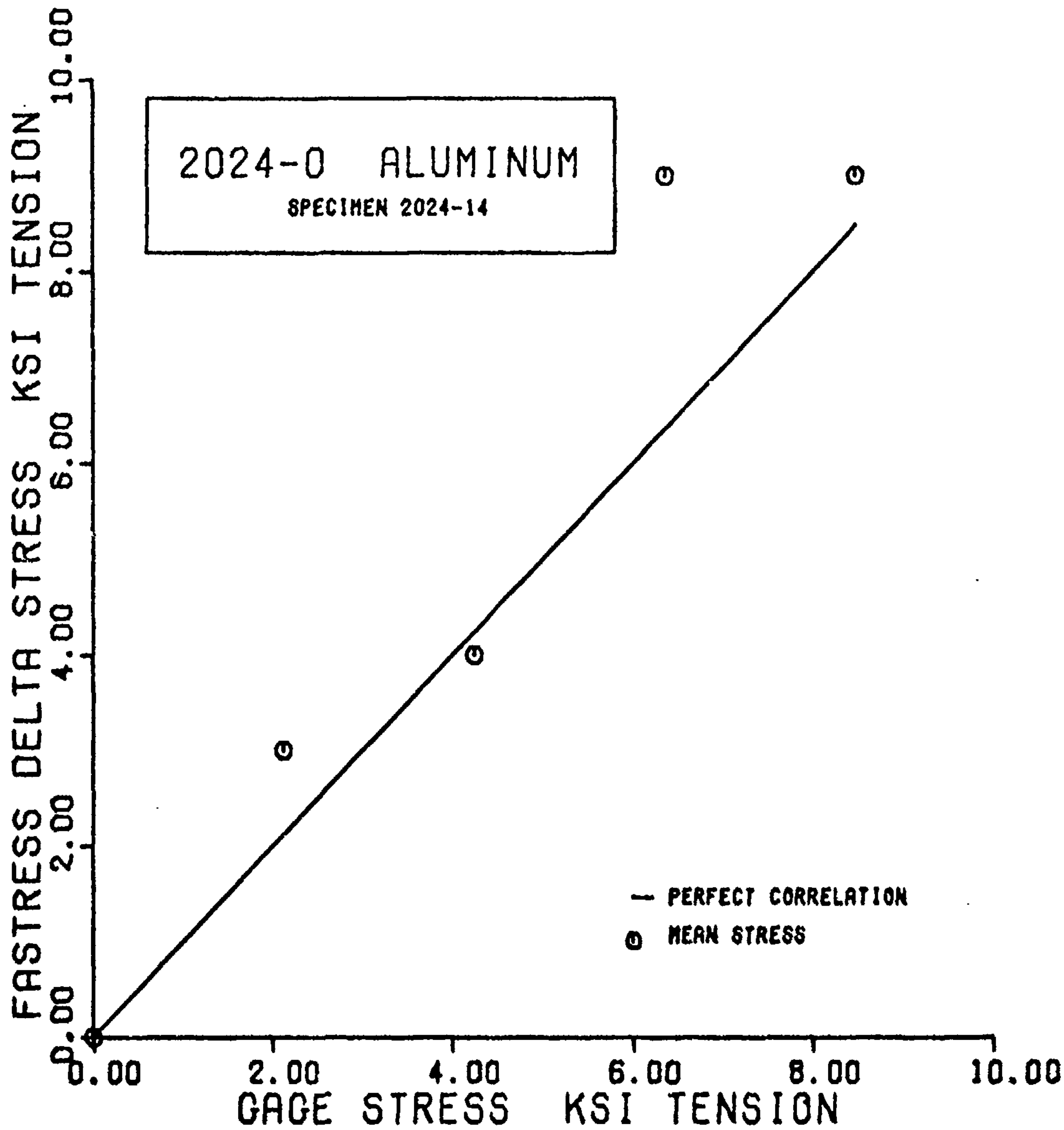

Fig. 11. Correlation Chart for 2024-0 Aluminum Alloy

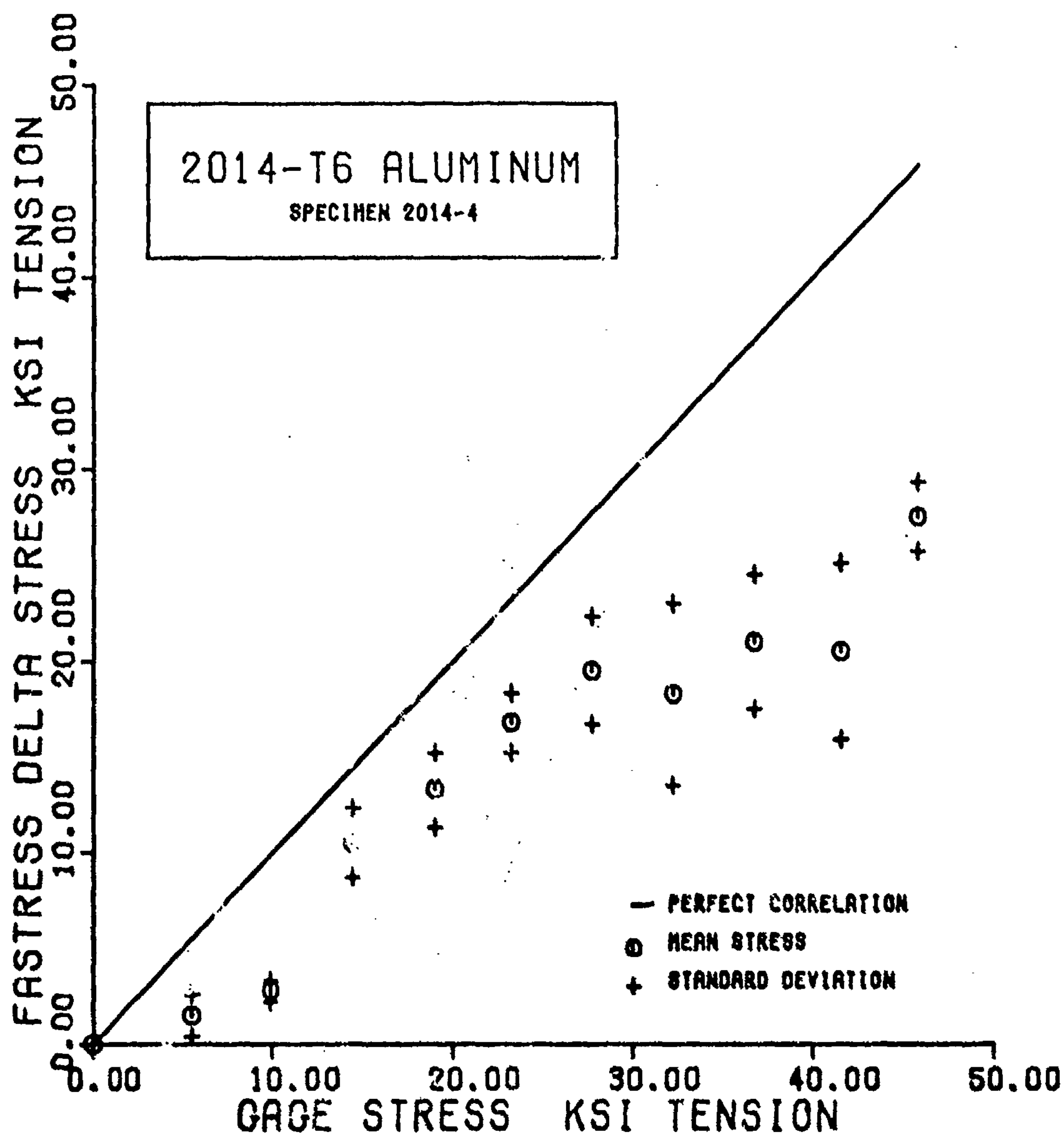

Fig. 12. Correlation Chart for 2014-T6 Aluminum Alloy

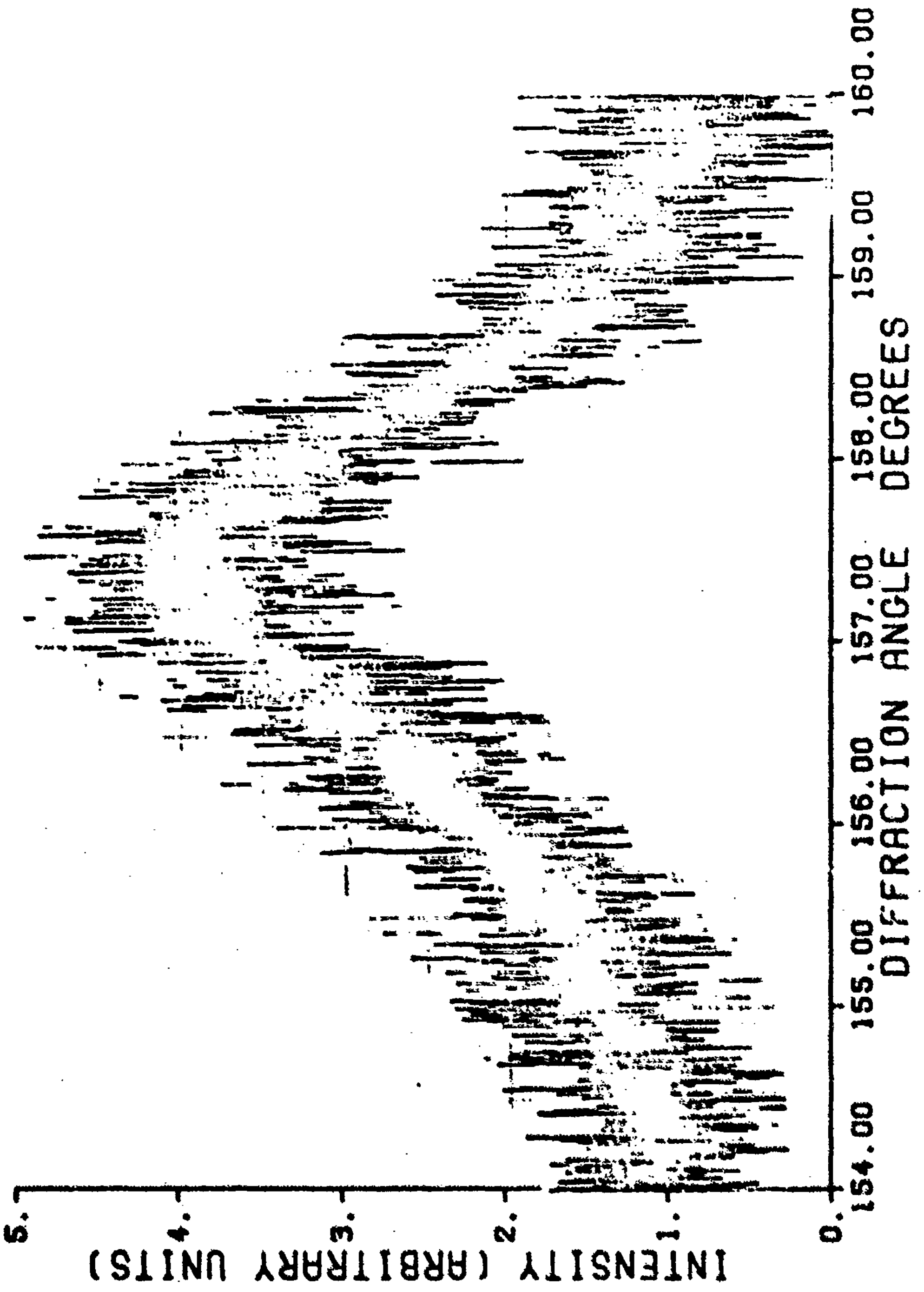

Fig. 13. Intensity Plot for ψ = 0-Degree System for 2014-T6 Aluminum Alloy

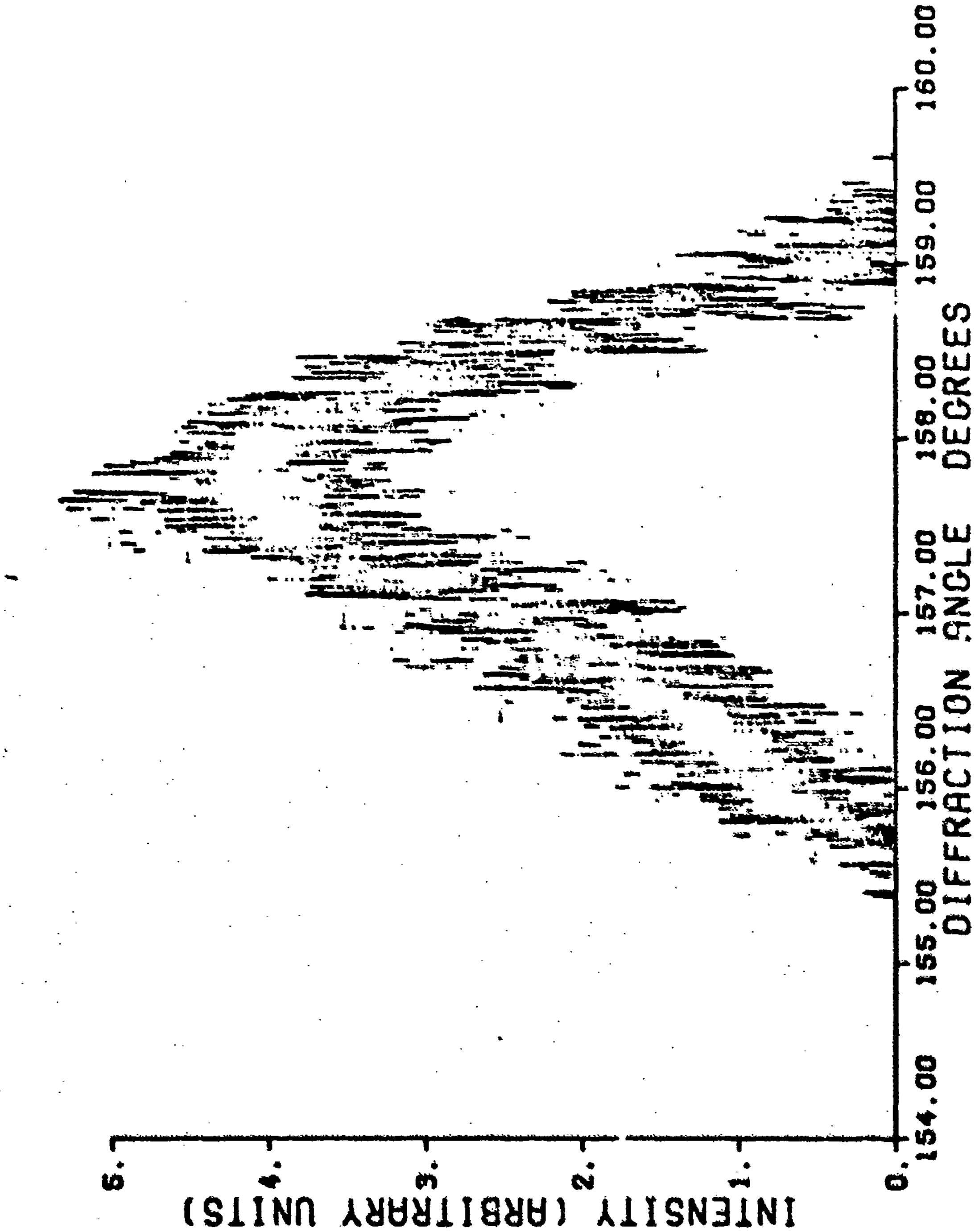

Fig. 14. Intensity Plot for ψ = 45-Degree System for 2014-T6 Aluminum Alloy (First Position)

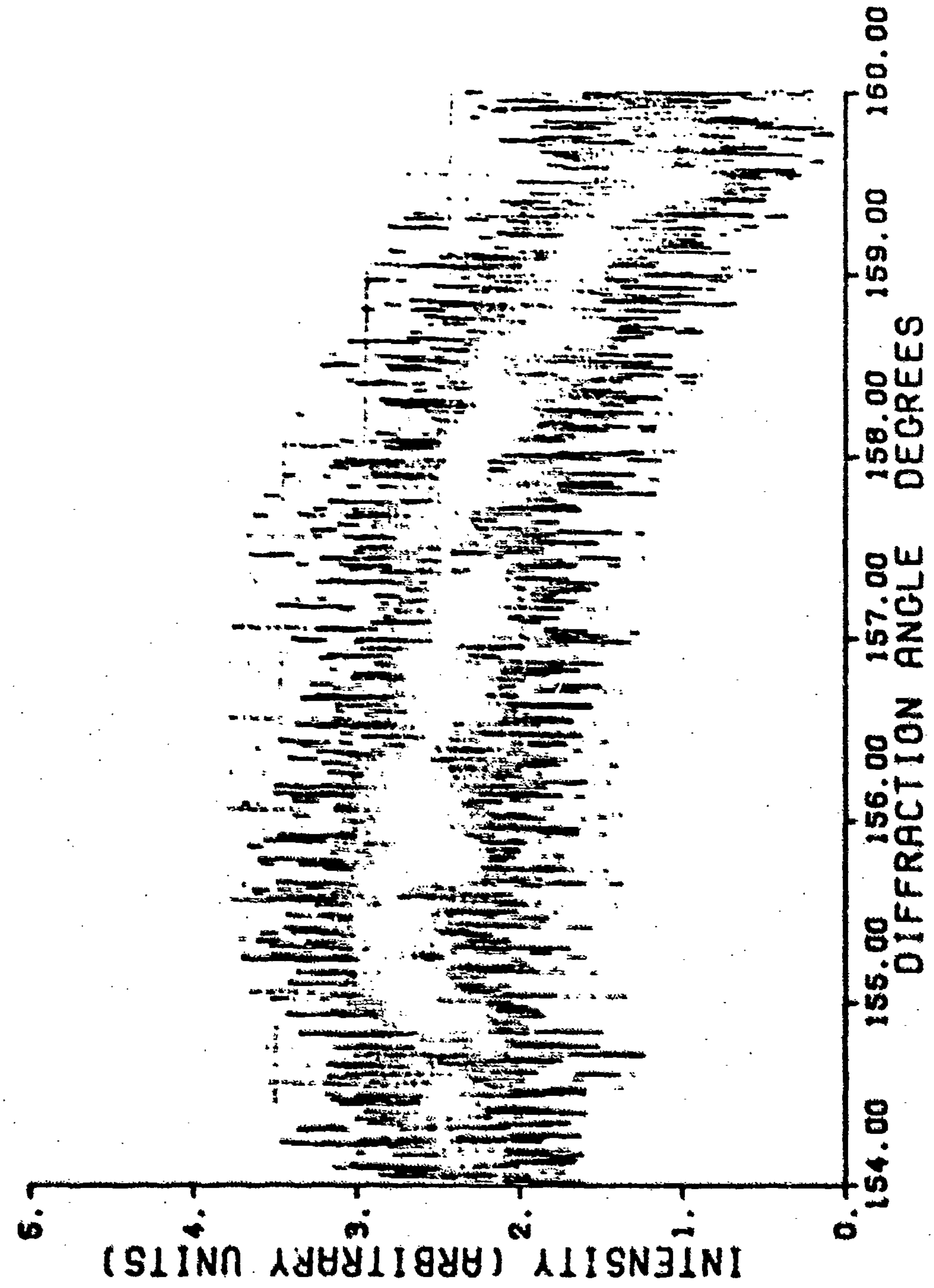

Fig. 15. Intensity Plot for ψ = 45-Degree System for 2014-T6 Aluminum Alloy (Second Position)

specimen on a conventional x-ray diffraction machine. It was concluded that it was not possible to accomplish successful measurement of the 2014-T6 specimen.

Fastress performance was very good on the 2024-T6 specimen (Fig. 16). Three tests were accomplished to evaluate reproducibility of the results. This indicated a standard deviation of 1,000 psi or less for each loading condition (Fig. 16). All Fastress values are lower than the gage values suggesting that a larger stress factor should be used. Plots of the diffracted x-ray intensity revealed that the pattern is very similar to the intensity pattern of the calibration standard (Fig. 17 and Fig. 18).

A partial test was accomplished on the 7178-T6 specimen. This indicated less stable operation than the measurement of the 2024-T6 specimen but provided useable results (Fig. 19). It appears that a larger stress factor should be used. Testing was prematurely terminated due to a strain gage failure.

One test of the 2024-T6 specimen with an anodic coating revealed less stable operation and greater Fastress error (Fig. 20). Use of a larger stress factor would reduce the error considerably.

Excellent correlation of Fastress and the gage stress resulted from a test of the 2024-T6 specimen that had been shot-peened (Fig. 21). Plots of the x-ray diffraction pattern reveal that the peaks are broader than the peaks for

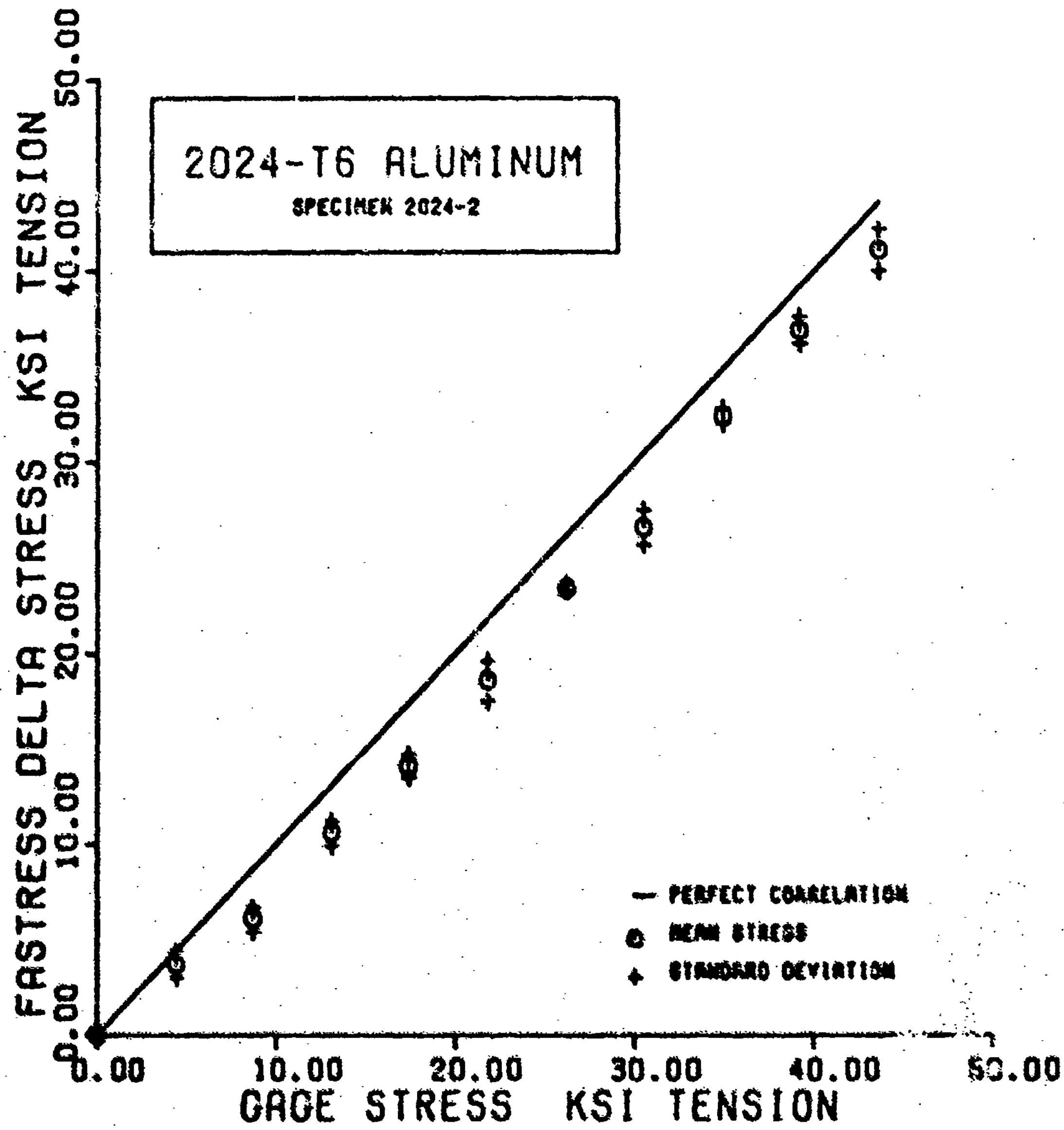

Fig. 16. Correlation Chart for 2024-T6 Aluminum Alloy

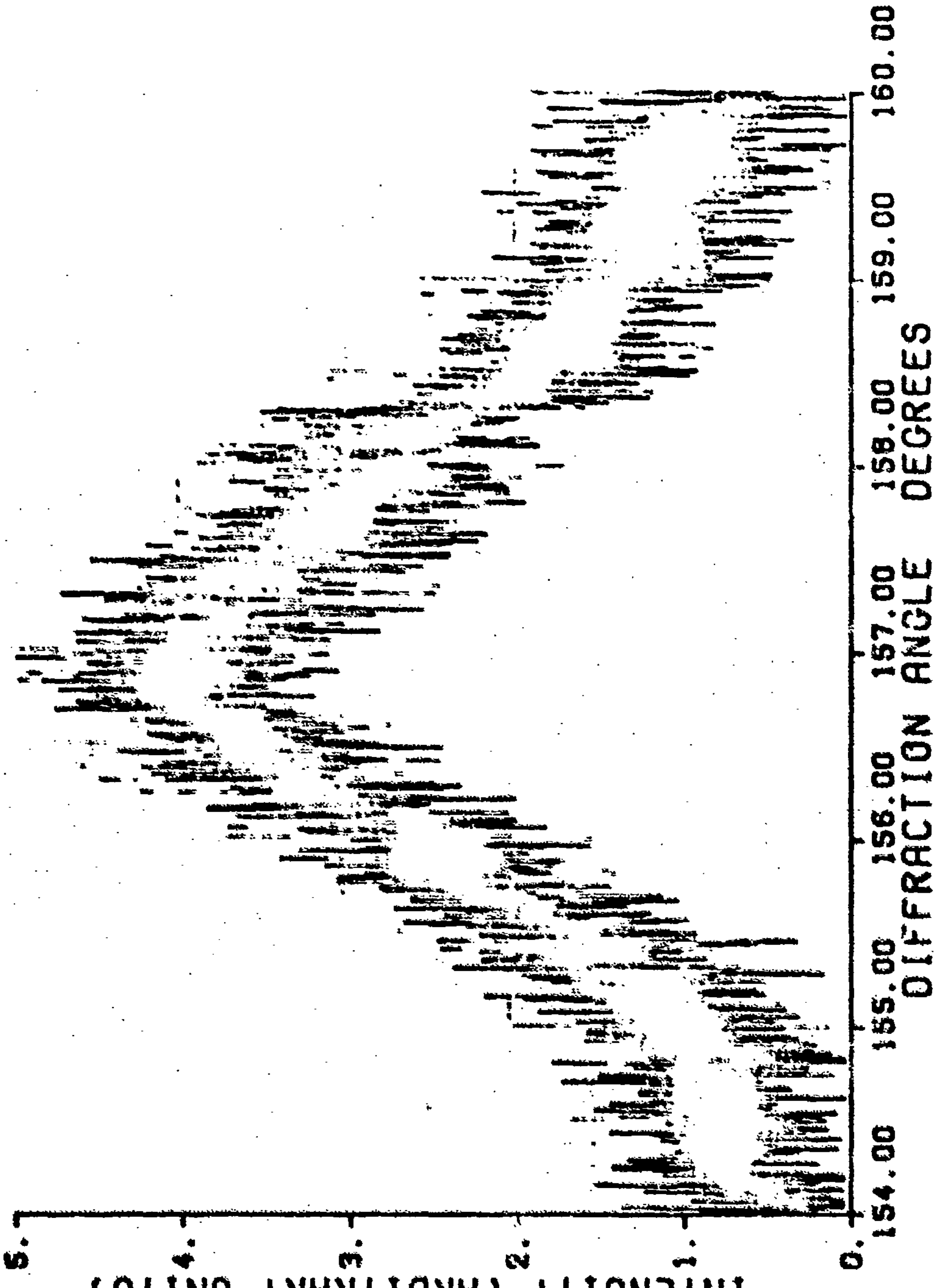

Fig. 17. Intensity Plot for ψ = 0-Degree System for 2024-T6 Aluminum Alloy

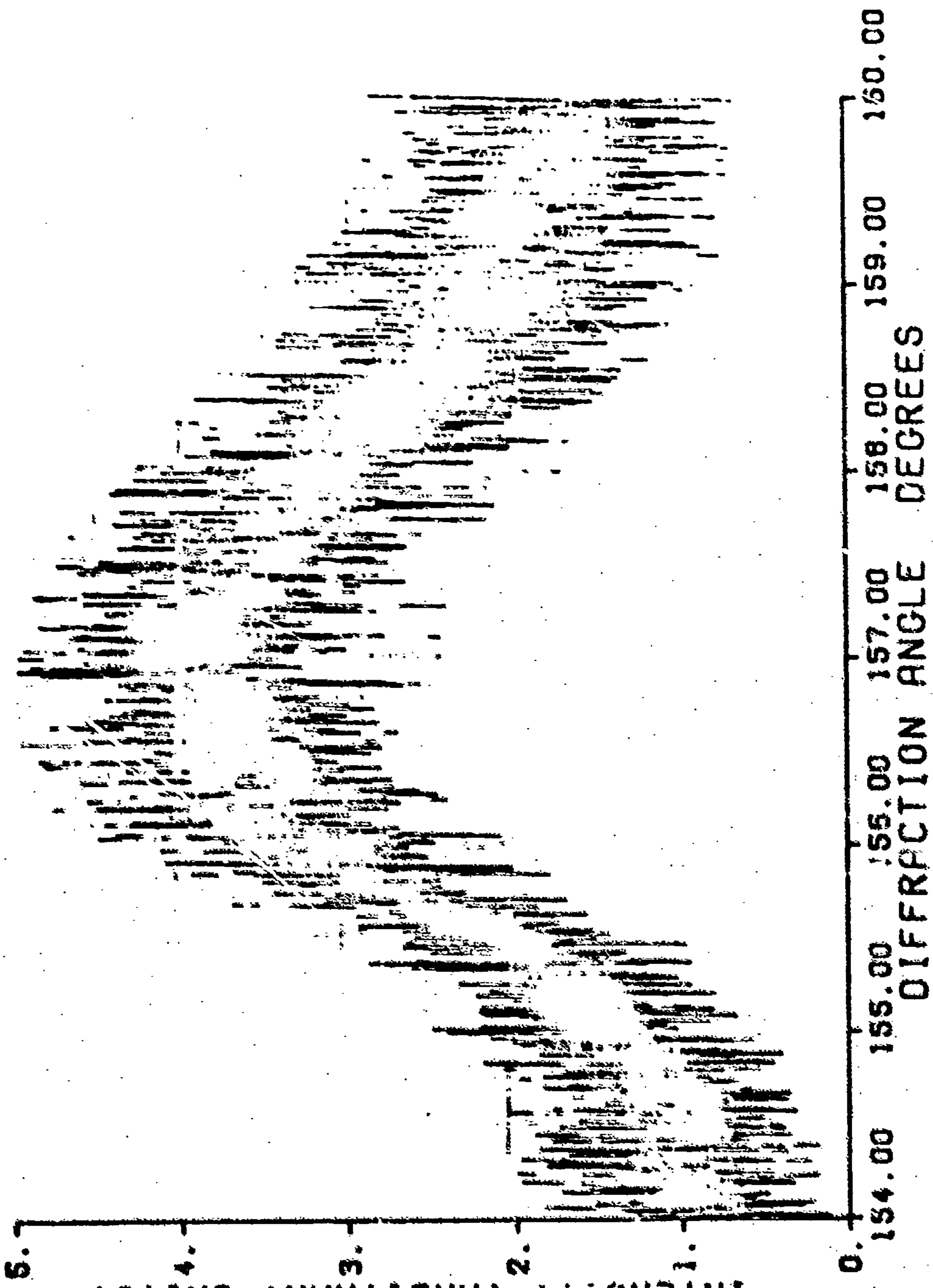

Fig. 18. Intensity Plot for ψ = 45-Degree System for 2024-T6 Aluminum Alloy

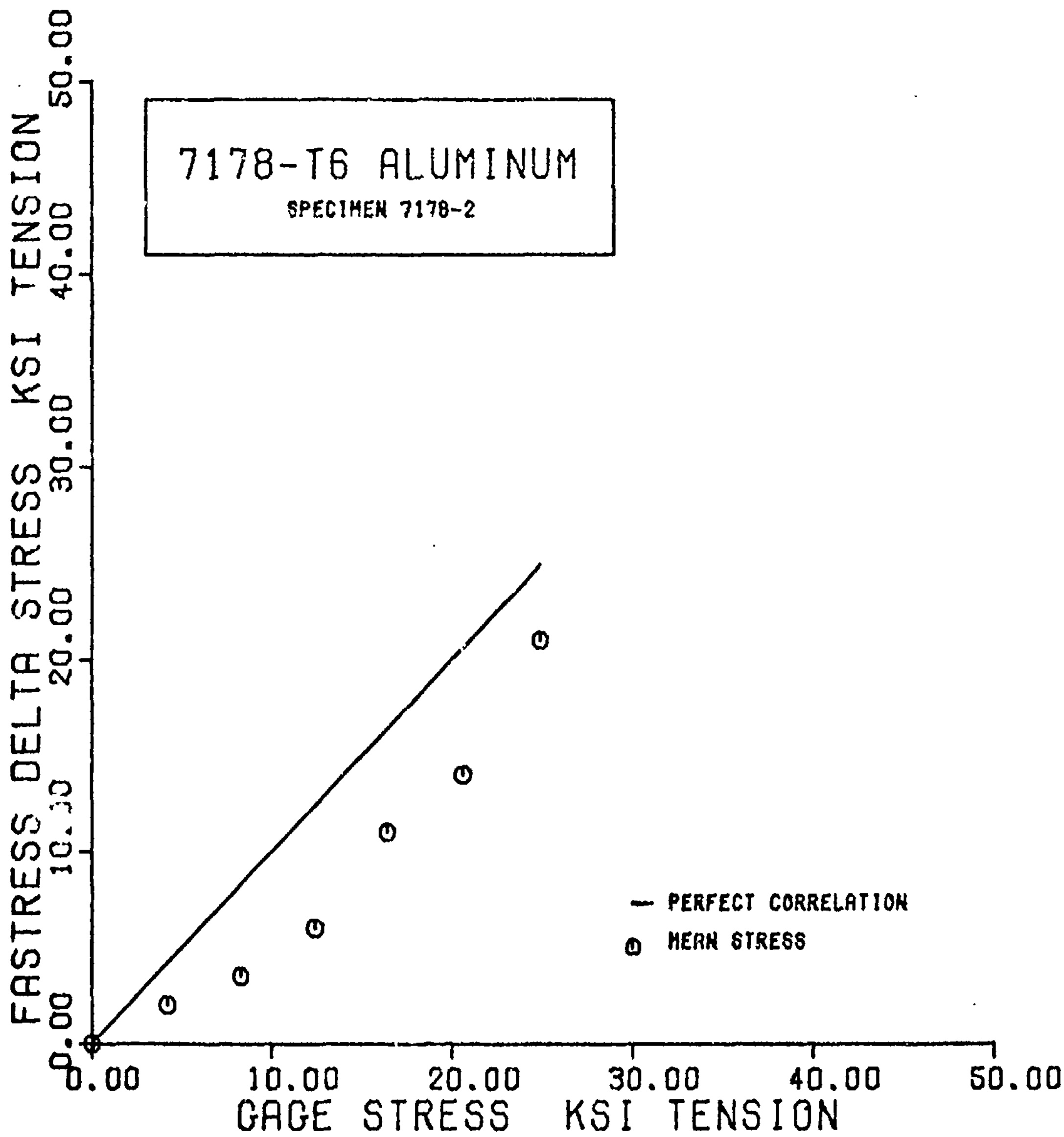

Fig. 19. Correlation Chart for 7178-T6 Aluminum Alloy

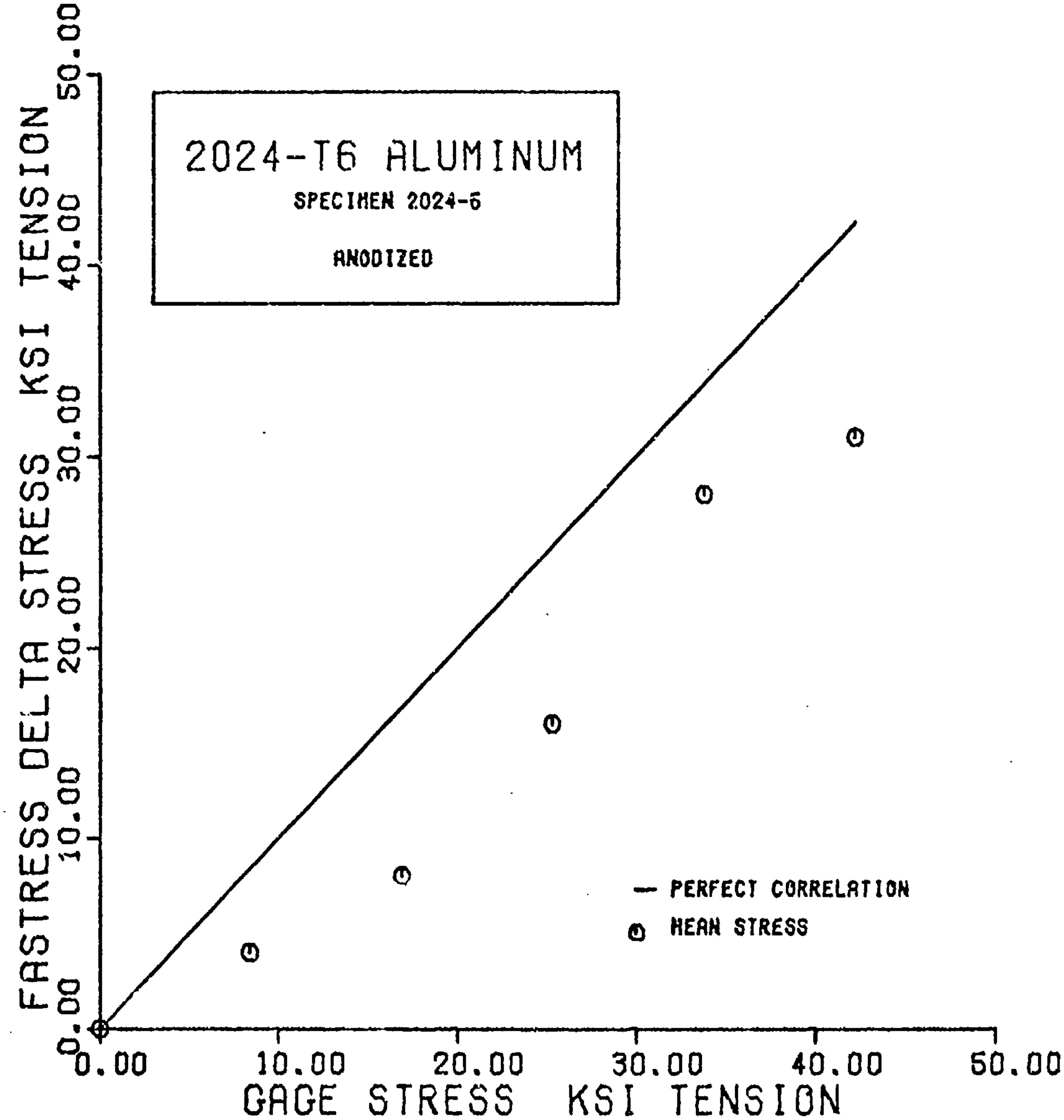

Fig. 20. Correlation Chart for 2024-T6 Aluminum Alloy with an Anodic Coating

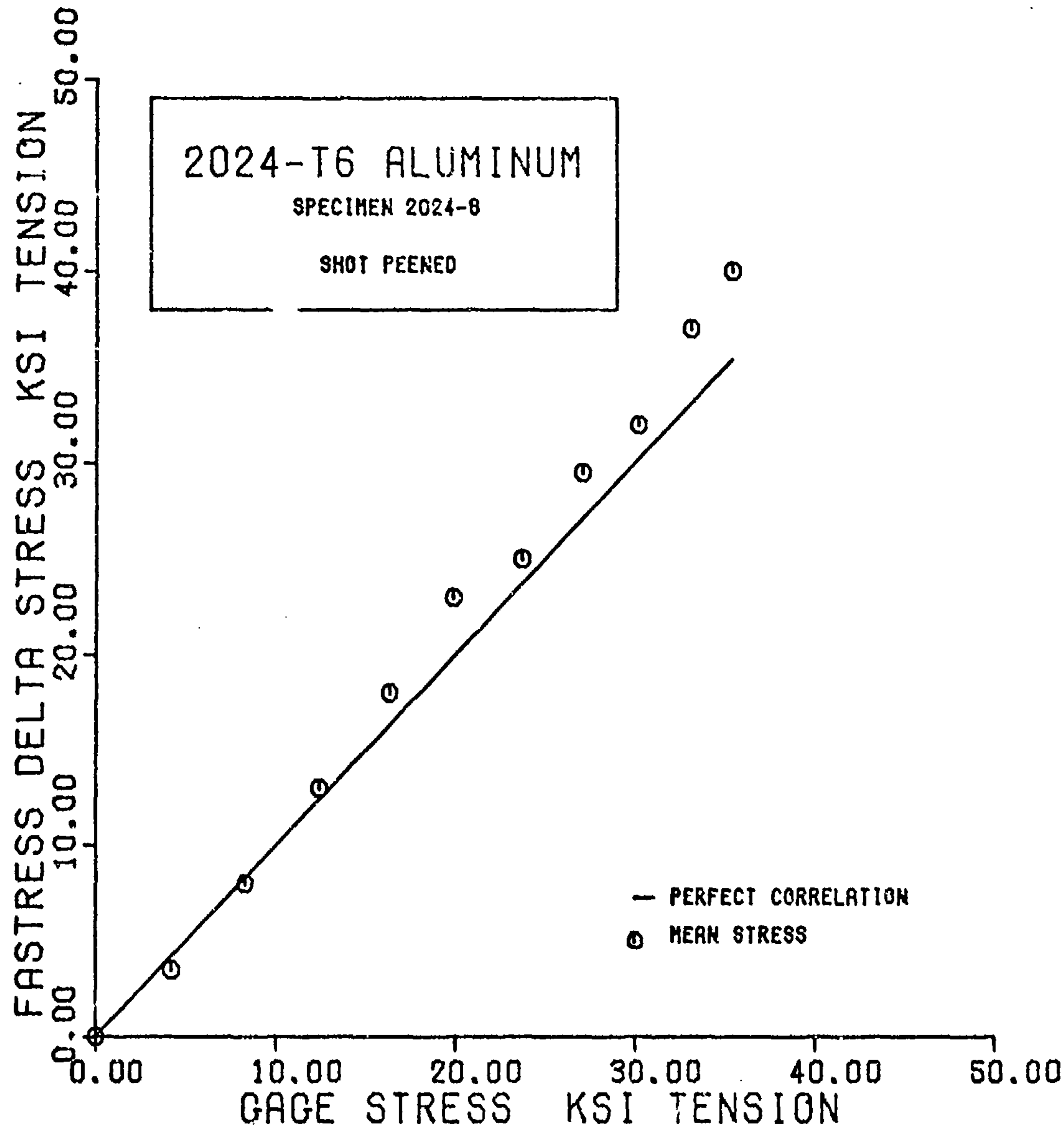

Fig. 21. Correlation Chart for 2024-T6 Aluminum Alloy with a Shot-Peened Surface

the unpeened 2024-T6 specimen (Figs. 22 and 23). The four-degree detector tube spacing appears optimum for this case. A slight reduction in the stress factor would improve correlation.

Two tests were accomplished on specimens that had been evaluated on a calibrated conventional x-ray diffraction stress measurement machine by Metcut Research Associates. The first specimen, 2024-1, was 2024-T6 aluminum alloy with a smooth surface. The Metcut measurement for this specimen was 7,100 psi compressive stress. The Fastress indicated a mean value of 8,000 psi compressive stress. The Second specimen, 2024-11, was a shot-peened sample of 2024-T6. The Metcut measurement for this specimen was 40,200 psi compressive stress. The Fastress mean stress reading was 42,500 psi. Note that both Fastress measurements are larger suggesting that the stress factor should be reduced.

Table II is a summary of results of all testing. The mean and maximum errors in terms of stress and per cent of applied stress are presented for each test specimen. All errors represent the difference between the Fastress measurement, using stress factor of 30,000 psi per degree, and the stress determined from strain gage measurements.

As noted above, Fastress was somewhat erratic in measurement of the annealed samples. Although the magnitude of the stress error is not large, the per cent error is very large because the applied stress is low. It should also be recognized that at the low level of applied stress, experi-

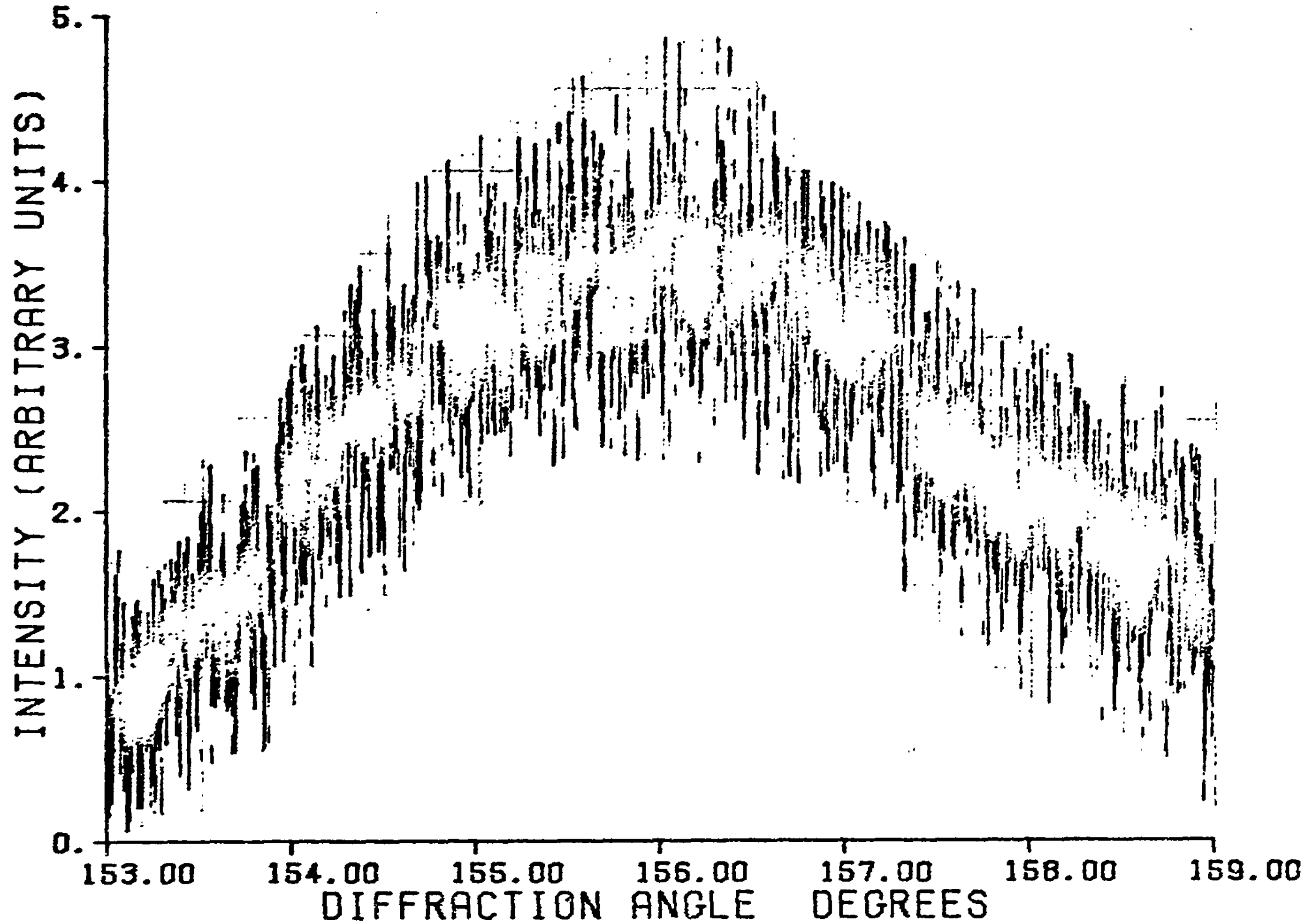

Fig. 22. Intensity Plot for ψ = 0-Degree System for 2024-T6 Aluminum Alloy with a Shot Peened Surface

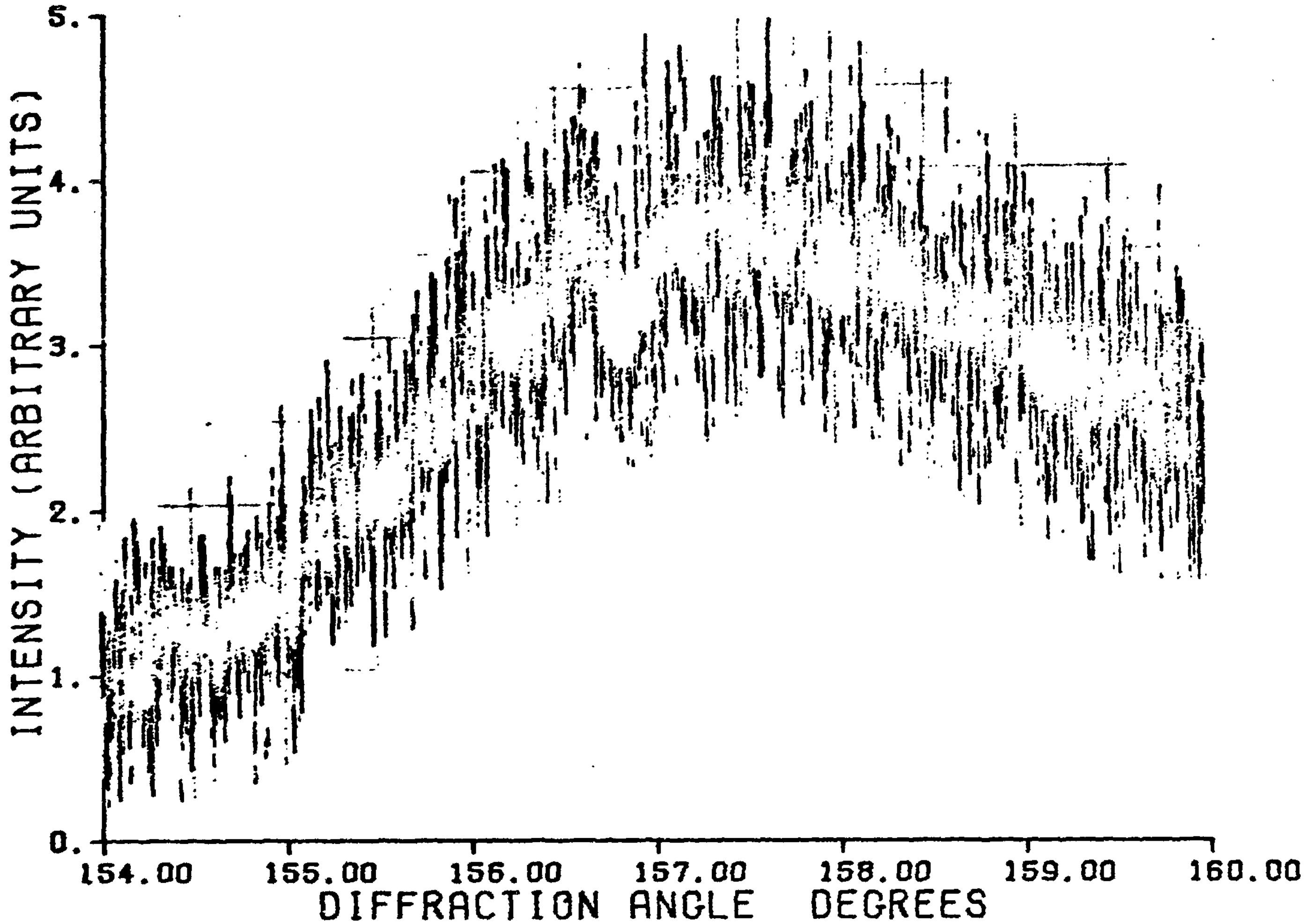

Fig. 23. Intensity Plot for Ψ = 45-Degree System for 2024-T6 Aluminum Alloy with a Shot Peened Surface

Table II

Summary of Results

Aluminum Alloy	Mean Error KSI	Maximum Error KSI	Mean Per cent Error	Maximum Per cent Error
1100	1.3	3.0	44	100
2014-O	1.9	3.6	39	89
2024-O	1.0	2.6	24	42
2014-T6	9.0	18.3	41	73
2024-T6	2.6	3.4	14	30
7178-T6	4.8	6.6	40	52
2024-T6 Anodized	7.9	11.2	37	53
2024-T6 Shot Peened	2.0	4.6	10	16

Error = Gage Stress - Fastress Delta Stress

$$\text{Per cent error} = \frac{\text{Gage Stress} - \text{Fastress Delta Stress}}{\text{Gage Stress}} \times 100$$

mental errors such as incorrect positioning of the specimen become very significant. The results of the annealed specimen testing are considered of limited value in the evaluation of Fastress.

The difficulty in measurement of stress in the 2014-T6 specimen has also been discussed. The results presented in Table II for this alloy are applicable only to this test specimen. They should not be considered representative of the 2014-T6 alloy in general.

Fastress performance on 2024-T6 was very good for both the smooth and shot-peened specimens. It should be noted that this may not be true for all parts manufactured from this alloy. This alloy may also exhibit the preferred orientation noted with the 2014-T6 specimen. Results of this study are applicable only if the intensity plot shapes for the material being tested are similar to those presented in this report.

Much larger error was noted for the 7178-T6 and 2024-T6 anodized specimens. The mean per cent error for both is close to the maximum per cent error. This indicates that much of the error can be eliminated by modification of the stress factor. The test of both specimens was somewhat limited and not considered sufficient for accurate determination of a suitable stress factor.

Table II suggests that without modification of the stress factor, Fastress should measure stress in aluminum alloys with a mean error of 8000 psi or less. This assumes,

of course, that the specimen is suitable for stress measurement by x-ray diffraction. More accurate selection of the stress factor should reduce the mean error to 2500 psi or less. This is less accurate than measurement of stress by conventional x-ray diffraction machines, but should be sufficient for many applications.

VI. Conclusions and Recommendations

Conclusions

Fastress did not operate properly when both x-ray systems were operated simultaneously. Manual switching of the systems to permit each system to position automatically eliminated the cross interference and produced suitable results.

The metallic specimen positioner provided with the Fastress machine causes severe error that can not be eliminated by machine adjustment. The problem is eliminated by using a nonmetallic positioner.

After the above modifications, Fastress measured applied stress in 2024-T6 and 7178-T6 aluminum alloys with a mean error of 8000 psi or less. This included 2024-T6 aluminum with anodized and shot peened surfaces. More accurate selection of the stress factor should reduce the error to 2500 psi or less.

Preferred grain orientation prevented accurate measurement of stress in the 2014-T6 aluminum alloy specimen. The intensity plotting feature of Fastress was useful in analysis of this problem.

Test of the annealed specimens of 1100, 2014, 2024 and 7178 aluminum alloys produced results of limited value. The annealed condition required use of low applied stress to prevent yielding. This resulted in a significant experimental error influence on the measurements.

Recommendations

The cause of the cross interference of the Fastress x-ray systems should be investigated. If the present gating system can not be modified to provide the required isolation, an automated switching system should be developed. This need only duplicate the manual switching of the x-ray source shutters and the detector arm drive motors used for this investigation.

The nonmetallic specimen positioner should be used for all future testing with Fastress.

The 30,000 psi per degree stress factor appears suitable for measurement of stress in 2024-T6 aluminum alloy with smooth or shot-peened surfaces. This may lead to considerable error in stress measurement of other alloys and surface conditions. Additional testing should be accomplished with the apparatus used for this study to better define variations in the stress factor.

Diffraction intensity should be plotted prior to stress measurements to insure that well defined peaks exist. Stress measurements alone may not indicate that a specimen is unsuited for measurement by Fastress.

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Appendix A

Fastress Controls

The following is a brief explanation of the Fastress controls and settings used as a baseline for this investigation.

1. X-Ray Tube Voltage and Current

Tube voltage is adjustable but was set at 35000 volts for all testing. Tube current is individually adjustable with a recommended maximum of 25 ma. Intensity of the incident x-ray is controlled by changing the current. Current settings were those required to produce a reading of 5 on the ψ = 0-degree activity meter and 8 on the ψ = 45-degree activity meter.

2. Detector Arm Position

Detector arm position is indicated in terms of diffraction angle (2θ). This is shown on a meter and by a mechanical scale on each arm.

3. Detector Tube Activity

Activity meters indicate intensity of the diffracted x-ray at each detector tube. Intensity may also be plotted on the strip chart recorder.

4. Detector Tube Balance and Sensitivity

Controls are provided to balance the tubes on each

detector arm. Detector tube voltage is also variable. Voltage was set at the point that produced a maximum reading on the activity meters.

5. Drive Motor Control

Switches are provided to select automatic or manual control of the drive motors. Response of the drive motors to the automatic control may be changed by adjustment of the servo gain control for each motor. A setting of 500 is recommended by the operating manual.

6. Recorder

Selector switches are provided to control the chart speed and scale factors for the integral recorder. A switch is provided to select residual stress or detector tube output (intensity) recording. One of the scale factor controls is to adjust the stress factor. The recommended setting for aluminum is 30000 psi per degree.

7. X-Ray Collimator

The size of the x-ray area on the specimen is controlled by changing collimator inserts. The 0.060-inch inserts are the largest available and were used for all testing.

8. Detector Tube Spacing

Detector tube spacing is manually adjustable. The adjustment is in terms of diffraction angle. A setting of four degrees is recommended for stress measurement of aluminum. This means that one detector is located at the detector arm

angle plus two degrees. The other is located at the detector tube angle minus two degrees.

Vita

Donald Henry Gray was born on 30 July 1936 in Batavia, New York. He graduated from high school in Le Roy, New York in 1954 and attended Syracuse University from which he received the degree of Bachelor of Mechanical Engineering in June 1958. Mr. Gray has been employed since graduation as a mechanical engineer for the Air Force Systems Command at Wright-Patterson Air Force Base, Ohio. He was assigned to the C-5A System Program Office as project engineer for the C-5A aircraft landing gear and mechanical equipment from 1965 until January 1972. He was then assigned to a similar position in the F-15 System Program Office until entering the School of Engineering, Air Force Institute of Technology, in June 1974.

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